Volume 53 November 1958 Number 7

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Six Dollars Fifty Cents a Year, One Dollar Twenty-five Cents a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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Indexed in the Industrial Arts Series.

LANCASTER PRESS, INC., LANCASTER, PA.

ch 3, 1879

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AND THE

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ECONOMIC GEOLOGY

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VOL. 53 NOVEMBER, 1958 NO. 7

IRON–TITANIUM OXIDE MINERALS, ROCKS, AND AERO-MAGNETIC ANOMALIES OF THE ADIRONDACK AREA, NEW YORK[1]

J. R. BALSLEY AND A. F. BUDDINGTON

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ABSTRACT

From studies of about 200 samples of metamorphic and igneous rocks from the Adirondacks it has been possible to relate the magnetic oxide assemblage to the lithology of the rocks and to their magnetic properties so that the magnetic anomaly produced by a particular rock type can be estimated. The intermediate members of the Fe_2O_3-FeO.TiO_2-(TiO_2) system are found almost uniformly to have *reverse* remanent magnetism and as much as several percent of disseminated magnetic oxides of this system may give rise to intense negative aeromagnetic anomalies. Where both magnetite and magnetic oxides of the Fe_2O_3-FeO.TiO_2-(TiO_2) system occur together in the same rock the resultant magnetic properties are such as to indicate that the magnetite grains have *normal* or positive remanent magnetization and the grains of the magnetic oxides of the Fe_2O_3-FeO.TiO_2-(TiO_2) system have *reverse* or negative remanent mag-

[1] Publication authorized by Director, U. S. Geological Survey.

netization. The value of the reverse magnetism of titanhematite, ilmenohematite, and rutiloilmenohematite is such that it can neutralize the total positive magnetism (remanent magnetism plus induced magnetism) of an equivalent or greater amount of magnetite. In the metamorphism of a pyroxene gabbro, giving a positive magnetic anomaly, to a hornblende-plagioclase amphibolite, the primary magnetite may be taken up by the hornblende, leaving ferrian ilmenite as the only oxide and the amphibolite may then give a neutral or negative anomaly.

Various investigators have suggested that the reverse magnetization of rocks is produced by a reversal of the earth's magnetic field at the time they cooled through the Curie point. This hypothesis does not seem to fit the geological, chemical, and magnetic data for the Adirondack rocks, for the reverse magnetization here appears to be related to the content of the intermediate members of the Fe_2O_3-FeO.TiO_2-(TiO_2) system. These mineral mixtures have the property of "self-reversal," that is, the ability to become magnetized in a direction opposite to that of the existing magnetic field. Until the existence of "self-reversal" can be disproved, one cannot state categorically that the reversed magnetization of a rock has been produced by a reversed field of the earth.

INTRODUCTION

THE U. S. Geological Survey in 1945 and 1946 made an aeromagnetic survey of about 3,000 square miles of the Precambrian rocks of the Adirondack area, New York, to further the development and discovery of magnetite iron ore deposits.

Subsequently the aeromagnetic data were compiled and magnetic contour maps prepared. The maps showed a close correlation with the known geology, so in 1949 a project was started by the U. S. Geological Survey to complete critical geologic mapping and to investigate the relationship between observed magnetic intensity and the various rock types and their content of magnetic material. These studies were directed particularly toward determining the origin of the numerous negative magnetic anomalies that are found in this region.

In this study, J. R. Balsley has been responsible for the geophysical work, A. F. Buddington for the geology and mineralogy, Joseph J. Fahey and Angelina Vlisidis for chemical analytical work, and Fred A. Hildebrand for X-ray determinations. All the chemical data of this report, not otherwise credited, are the work of Joseph J. Fahey and Angelina Vlisidis.

Preliminary studies showed that the bedrock underlying the negative anomalies could be classified into three types on the basis of accessory oxides. One type of rock contained only titaniferous hematite; a second type, magnetite and titaniferous hematite (with ilmenite microintergrowths) with or without associated grains of ilmenite (with hematite microintergrowths); and a third type, ilmenomagnetite and ilmenite. It was assumed in the beginning that the magnetite played the major role in giving rise to negative anomalies. We therefore attempted to determine if there was any correlation between the negative anomalies and either the chemical composition of the magnetite or the nature and texture of the mineral intergrowths within it.

A magnetite concentrate was made from each of 140 different rock samples

from beneath both negative and positive magnetic anomalies. Chemical analyses were made on all magnetite concentrates for titanium, on 28 for MnO, on 19 for V_2O_3, and 3 for MgO. The negative anomalies did not correlate with these variations in the composition of the magnetite. Neither could we find a correlation with the amount or texture of the intergrowth of ilmenite in magnetite, as studied at moderate magnifications.

We then considered the hypothesis that the thermal history of the magnetite might be a factor. A study of the data accumulated on the percent of TiO_2 in the magnetite or ilmenomagnetite from many different kinds of rocks showed that the percent of TiO_2 varied systematically with the temperatures at which it was inferred the rocks had formed (9). The composition of the magnetite and the geologic history indicates that it was formed either above its Curie point or locally only slightly below. No correlation was found between the temperature of formation of magnetite and the negative anomalies.

During the course of the study of the magnetite much work had been done in determining the nature of the nonmagnetic oxide minerals by chemical analysis, study of polished surfaces, and X-ray mineral determinations. Some of the negative magnetic anomalies are produced only by titaniferous hematite so we next tested the hypothesis that all the *intermediate* members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) series had reverse remanent magnetization of sufficient intensity to overcome the normally-directed induced and remanent magnetization of an equal or greater percentage of magnetite. This hypothesis seems to satisfy the various chemical, magnetic, mineralogical and physical data we have collected for these rocks.

We now have for each of 154 samples the percent of oxides in the rock, the quantitative ratio of the magnetic oxide concentrate to the nonmagnetic iron and titanium oxide concentrate, the percent of FeO, Fe_2O_3, and TiO_2 in the magnetic and the nonmagnetic concentrate where both are present, and the magnetic susceptibility and magnitude and orientation of the remanent magnetization. We also have the amount and chemical analysis of the magnetic oxide alone in an additional 41 samples. Only part of this data, however, will be given here. All analyzed specimens have been checked with thin sections and a total of 450 polished surfaces. The mineralogy and field magnetic data have been further checked by study of an additional 300 polished surfaces from more than two hundred different localities. X-ray identifications were made for 31 magnetic concentrates and 43 nonmagnetic concentrates.

Aeromagnetic total intensity contour maps with superimposed geology have been published for the Stark and parts of the Russell and Childwold quadrangles (7), for the Oswegatchie quadrangle (5), and for the Cranberry Lake quadrangle (6). These maps afford the basis for much of our discussion of the aeromagnetic anomalies.

MAGNETIC MINERALS

As a result of our chemical, microscopic, and X-ray work, we have found that the minerals that need to be considered in relation to the magnetic phenomena we are studying are those belonging to the following series:

Fe_3O_4-FeO.TiO_2-(2 FeO.TiO_2); Fe_3O_4-FeO.TiO_2-(Fe_2O_3); and Fe_2O_3-FeO.TiO_2-(TiO_2). The oxides in brackets are subordinate in the systems. The pure minerals, hematite, rutile, and ilmenite, are usually described as paramagnetic minerals, that is, that they have low magnetic susceptibility and are, therefore, "nonmagnetic." Our work has shown that the intermediate solid solution members of the equivalent chemical compounds or exsolved microintergrowths of these minerals can be similarly described but that in spite of their nonmagnetic characteristics they have very strong remanent magnetization.

Pyrrhotite is also a magnetic mineral and occurs locally in small amounts in the skarn deposits or as a very minor accessory mineral especially in the pyroxene syenitic and mafic rocks. It apparently does not play an essential role in the aeromagnetic anomalies of the Adirondacks and will not be considered further. An excellent general discussion of the subject of mineralogy and rock magnetization has recently been given by Nicholls (21).

The following terms will be used for the magnetic oxide minerals pertinent to our problem. The term oxides will here include only the iron and iron-titanium oxide minerals and not quartz or the silicate minerals. In figures 5, 6, and 7 the term oxides means oxide minerals. A mineral that is a one-phase solid solution will be named according to the minor metal as titan-hematite (for hematite with 5 to 10 percent TiO_2 in solid solution) or titan-magnetite for magnetite with titanium in solid solution; where there are micro-intergrowths the term for the two or three-phase mixture will be a hybrid name such as ilmenhematite for microintergrowths of ferrian ilmenite in titan-hematite, hemoilmenite for intergrowths of titanhematite in ferrian ilmenite or ilmenomagnetite for microintergrowths of ilmenite in magnetite. Terms such as titaniferous magnetite will be used as a general one which does not carry any implication as to whether a solid solution titanmagnetite or the microintergrowth ilmenomagnetite is involved. Ulvöspinel (2FeO.TiO_2) has been shown by Ramdohr (23) to be a common exsolution microintergrowth in magnetite of certain kinds of rock.

A classification of the minerals as used in this paper is given below. The terminology has been adopted to suit our problem and the situation as found in Adirondacks and is not intended as a general system. It does not take into account slight variations which would result if the small amounts of Al_2O_3, MgO, MnO, and so on, actually present were known and considered.

Single Phases

Magnetite, almost wholly Fe_3O_4.

Titanmagnetite, magnetite with titanium compounds in solid solution.

Hematite, almost wholly Fe_2O_3.

Subtitanhematite, Fe_2O_3 with 1.5 to 5 percent TiO_2 (as FeO.TiO_2 or TiO_2 or both).

Titanhematite, Fe_2O_3 with 5–10 percent TiO_2 (as FeO.TiO_2 up to about 13 percent plus excess TiO_2 up to about 3 percent).

Martite, hematite (Fe_2O_3) as a secondary alteration of magnetite.

Ilmenite, $FeO.TiO_2$ with up to about 6 percent Fe_2O_3 and perhaps a little TiO_2 in solid solution.

Ferrian ilmenite, $FeO.TiO_2$ with 6 to 13 percent Fe_2O_3 and up to perhaps 3 percent excess TiO_2 in solid solution. The terms ferricilmenite and ferrilmenite have also been used for this mineral. We are adopting ferrian ilmenite as suggested by M. Fleischer.

Ulvöspinel, $2\ FeO.TiO_2$.

Rutile, almost wholly TiO_2.

Microintergrowths

Ilmenomagnetite, magnetite with microintergrowths of ilmenite.

Ilmenohematite, titanhematite with microintergrowths of ferrian ilmenite or hemoilmenite.

Hemoilmenite, ferrian ilmenite with titanhematite or ilmenohematite in microintergrowth.

Ilmenorutilohematite, titanhematite with exsolved microintergrowths of ferrian ilmenite or hemoilmenite and rutile.

Rutilohematite, titanhematite with microintergrowths of rutile or exsolved grains.

Metailmenite, microaggregate of hematite and rutile and/or anatase resulting from oxidation of ilmenite; fabric is a micro-patchwork or moiré texture as distinguished from crystallographically oriented intergrowths of rutilohematite. Arizonite, originally described as a mineral, has been shown (22) to be a mixture produced by weathering. This is in part comparable to what is here called metailmenite. In part it may result from relatively low temperature hydrothermal oxidation.

The amount and size distribution of the exsolved microintergrowths of ferrian ilmenite in titaniferous hematite in general varies systematically as the percent of TiO_2 increases. The exsolved microintergrowths of ferrian ilmenite in titaniferous hematite with 12–16 percent TiO_2 are stringlets of one narrow size range, with 17–21 percent TiO_2 there are two distinct size ranges, and with 21–25 percent TiO_2 three separate size ranges. The largest ferrian ilmenite intergrowths of the last group has titanhematite in turn as exsolved intergrowths. Where TiO_2 in excess of that which can be recalculated as ilmenite occurs to the extent of more than about 3.5 percent it appears as rutile microintergrowths or as exsolved grains on the borders of the titaniferous hematite.

The titaniferous magnetites have been previously discussed (8, 9).

Variation of Mineral Assemblage with Intensity of Oxidation.—Three chemical components, FeO, Fe_2O_3, and TiO_2 are fundamentally involved in our problem. These oxides form a series of mineral assemblages that are in part dependent upon the intensity of oxidation, which, in turn, is in part dependent upon the composition of the system and the temperature and pressure at which the minerals form. The series of diagrams in Figure 1 show

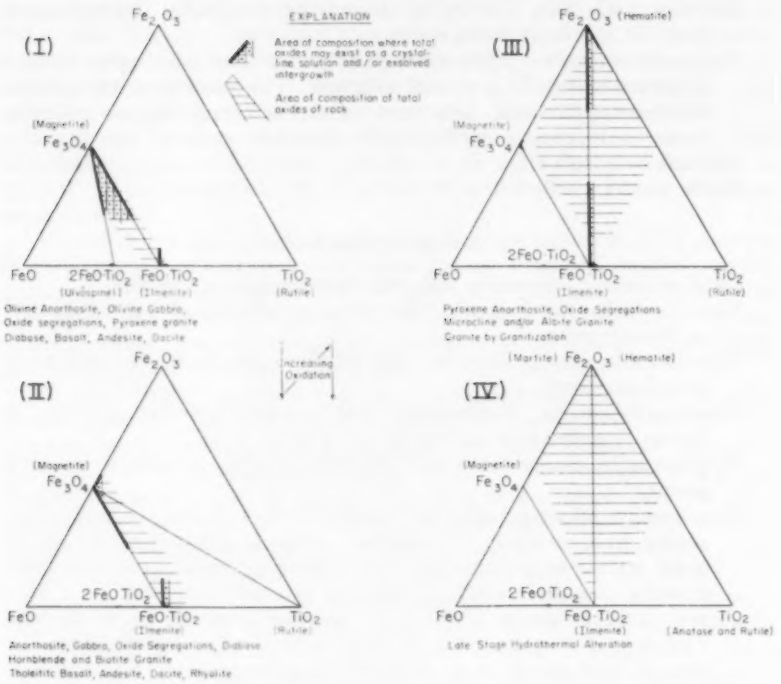


FIG. 1. Variation of mineral assemblages with increasing intensity of oxidation.

the various mineral assemblages that we have found to be present in the different rock types we have studied. It is recognized that these diagrams do not represent all kinds of assemblages that have been described but it is thought that they do exemplify those essential for our problem in the Adirondack rocks. It may be deduced from the successive diagrams that an oxide assemblage with a given ratio of Fe to Ti may consist of (I) magnetite (with exsolved ulvöspinel) and ilmenite; (II) magnetite (with exsolved ilmenite) and ilmenite or ferrian ilmenite with or without rutile; (III) magnetite, ferrian ilmenite (with exsolved hematite intergrowths) and titanhematite (with exsolved ferrian ilmenite intergrowths); and (IV) magnetite, martite, and ilmenite (in part altered to metailmenite). The successive assemblages represent formation at increasing levels of oxidation and in a general way at successively lower temperatures. Intense oxidation of a mixture potentially capable of forming ilmenomagnetite and ilmenite may also yield ilmenohematite or rutilohematite.

The vital role of the intensity of oxidation in determining the mineral assemblage of rocks with the same content of iron and titanium can be demonstrated in the Adirondacks by rocks resulting from the progressive granitiza-

tion of biotite quartz plagioclase gneiss to sillimanitic microcline granite-like gneiss. There are all gradations in intensity of oxidation of the iron from the biotite quartz plagioclase gneiss in which the iron is wholly in the biotite to an intensely granitized facies in which the only mica is a very little muscovite and the only oxides are rutilohematite plus or minus rutile as indicated in Table 1. In the physicochemical environmeent of this oxidation process, the

Table 1 - Variation of minerals with intensity of oxidation during granitization

	% FeO	% Fe_2O_3	% TiO_2	Minerals
Average composition of biotite quartz plagioclase gneiss. (Engel and Engel, 1953, 1063)	4.12	1.31	0.67+	Biotite (18%)
(A) Sillimanitic microcline granite gneiss, moderately oxidized*	0.92	3.99	0.54	Ilmenomagnetite Ilmenohematite
(B) Sillimanitic microcline granite gneiss, strongly oxidized*	0.45	4.64	0.76	Titanhematite with slight ilmenite intergrowth ± rutile
(C) Sillimanitic microcline granite gneiss with most intense oxidation*	0.07	4.86	0.68	Rutilohematite Rutile

* Analyst, Angelina Vlisidis. The analyses of A, B, and C are of the total oxide minerals only. There is a little biotite or chlorite in the rocks of A, B, and C which would increase the iron and titanium slightly for the rock as a whole. A and B are averages of 12 and 16 separate samples.

\+ Corrected from original to accord with more recent work by Engel and Engel (personal communication)

TiO_2 oxides are more soluble in hematite than in magnetite so in a broad sense as the percent of magnetite relative to hematite increases, the percent of TiO_2 in the hematite increases rapidly. At Benson Mines two samples of analyzed ore each had 2.1 percent TiO_2; in ore with only 22 percent magnetite the associated mineral is subtitanhematite with 2.65 percent TiO_2 whereas in ore with 80 percent magnetite the associated mineral is titanhematite with 10 percent TiO_2.

We also find that, depending upon the degree of oxidation, the iron, even where its total quantity is nearly the same in two different granites, may be present in one in femaghastingsite with magnetite predominant over ferrian ilmenite and the rock have a positive magnetic anomaly, and in the other in a more iron-rich hornblende (ferrohastingsite) with ferrian ilmenite pre-

dominant over magnetite and a negative magnetic anomaly (Table 1a). Similarly, the mafic minerals in a pyroxenic gneiss may either be ferrohypersthene with magnetite predominant over ferrian ilmenite or a more ferrous iron-rich orthopyroxene (eulite) with ferrian ilmenite predominant over magnetite. Where magnetite is present the total oxide minerals will in general be larger than where ferrian ilmenite only is present.

The martite and metailmenite in general are unrelated to the present surface and to weathering and their formation is inferred to be largely of hydrothermal origin. Martitization of magnetite in association with ilmenohematite

Table 1a. Effects of Intensity of Oxidation on Distribution of Fe and Ti Oxides Between Silicates and Oxide Minerals and on Sign of Remanent Magnetism

	% of Fe and Ti oxides in rock				% of oxides as oxide minerals of rock			Remanent Magnetism
	Fe_2O_3	FeO	TiO_2	Total	Fe_3O_4	$FeO{\cdot}TiO_2$ $+Fe_2O_3$	Total	Inclination
Femaghastingsite microperthite granite NE of Scanlons, Oswegatchie Q.	1.60	1.40	0.37	3.37	0.74	0.42	1.16	+68°, N
Ferrohastingsite microperthite granite, west of Briggs, Oswegatchie Q.	1.32	1.93	0.32	3.57	0.32	0.65	0.97	-54°, R
Femaghastingsite granite gneiss Stark Q.	2.43	3.29	1.24	6.90	1.60	0.50	2.10	+52°, N
Ferrohastingsite granite gneiss, Stark Q.	1.59	4.17	0.53	6.29	0.02	0.46	0.48	-54°, R
Ferroaugite-ferrohypersthene (En_{40} Fs_{60}) quartz-bearing syenite gneiss Tupper Lake Q.	1.73	4.10	1.01	6.84	1.27	0.91	2.18	+51°, N
Eulite ($En_{18}Fs_{82}$) quartz syenite gneiss, SW part of Tupper Lake village	1.03	4.49	0.68	6.20	0.31	0.96	1.27	-71°, R

N - Normal orientation of remanent magnetism
R - Reverse orientation of remanent magnetism

does not normally occur until the latter is the major or predominant oxide. The occurrence of metailmenite for the most part as a replacement of only the largest lamellae of intergrowths in ilmenohematite suggests possibly that it formed before the exsolution of the smaller ilmenite intergrowths.

Magnetite may be replaced by martite without any contemporaneous alteration of ilmenite, and ilmenite may be altered to metailmenite without concomitant alteration of magnetite. We have not ascertained the basis for these two independent types of alteration. On the other hand, both martite and metailmenite that are abundant in samples of rock from three places in

the bed of the Raquette River seem to be the product of weathering. There is more hematite than normal in such metailmenite.

Magnetic Properties of the Oxide Minerals.—The two magnetic properties that are important to this study are the magnetic susceptibility and the permanent or remanent magnetization. Magnetic susceptibility (K) is a dimensionless number that represents the ability of a material to assume a magnetization when in a magnetic field. Thus when the magnetic susceptibility is high a material would be considered "magnetic" by the geologist for his magnet induces a strong magnetization in the material and causes it to be attracted to the magnet. The direction of this induced magnetization is normally in the direction of the magnetizing field.

The permanent or remanent magnetization (R. M.) of a material is that magnetization in it which exists independent of any external magnetizing field and is the same as that of an ordinary magnet. It has a measureable intensity or moment and a direction fixed with respect to the piece of material.

A natural remanent magnetization for the oxide minerals of many rocks may be acquired during cooling in the earth's magnetic field within a critical but substantial temperature range just below their Curie points (17, p. 123–192) the temperature below which a material becomes magnetic. The temperature range during the metamorphism of the rocks to gneisses is inferred to have been between 450° ± 100° on the northwest and perhaps as high as 700° C in the core of the Adirondacks, and the minimum temperature of consolidation of the major igneous rocks is estimated as above 650° C. All the rocks have therefore had opportunity to acquire a remanent magnetization though the cooling period would have been a matter of millions of years rather than hours or hundreds of years as in lava flows and thin sills. The exsolution of intergrowths in the titanhematite and ferrian ilmenite and in the ilmenomagnetite probably took place in part at least within the same temperature range as the development of the remanent magnetization.

The total natural magnetization of a rock in place is the vector sum of the remanent or permanent magnetization (I_R) and the induced magnetization (I_{HK}). The latter is the product of the local earth's field and the magnetic susceptibility. There is, of course, a slight variation in the value of the earth's field and the magnetic inclination within the area as large as that under discussion. For practical purposes, however, the magnitude of the earth's field for the northwest Adirondacks has been taken as 0.58 oersted and the angle of inclination as 74°.

Data on the variation of magnetic properties with variation in the mineralogy are shown in Tables 2, 2a, and 2b. To simplify the tables, the values are shown as a single percentage but actually the data are averages over a small range. The magnetic observations were made on several cores from a single rock sample. Different cores from the same sample of the gneisses may vary widely in magnetic properties and for many of the samples the number of cores was inadequate to ensure reliable averages. Furthermore the percent of magnetic and nonmagnetic concentrates were determined on a different sample from that used for the magnetic determination. Both samples were chosen with care for similarity and came from blocks adjacent to each

Table 2 - Variation of magnetic properties with variation in mineralogy and lithology
Northwest Adirondacks

IGNEOUS ROCKS AND ORTHOGNEISSES

Field number of samples[a]	Minerals[a]	Wt. % total oxide minerals in rock	Fe_2O_3 as % of total oxide minerals	* Non-magnetic oxides as % of total oxide minerals	Susceptibility in units of 10^{-3} per gram oxide minerals	Computed induced magnetization in units of 10^{-3} per gram oxide minerals (I_{MK})	Remanent magnetization in units of 10^{-3} per gram oxide minerals (I_R)	I_R/I_{MK}	Inclination of remanent magnetization
Granite and Granite Gneiss									
134,196 252	Ferrian ilmenite	0.42	7	93	3.4	2.0	10	5.0	-79°
207,245	Ferrian ilmenite	0.395	7	93	8.2	4.7	11.7	2.5	-51°
190,260	Ferrian ilmenite (Ilmenomagnetite)	0.82	18.4	81.6	19.8	11.5	5.1	0.5	-37°
30-A,51, 100,239	Ferrian ilmenite Ilmenomagnetite	1.26	63.0	37.0	28.1	16.3	12.9	0.8	+9°
183,238	Ilmenomagnetite (Ferrian ilmenite)	0.99	81.2	18.8	35.2	20.5	3.7	0.19	+27°
6A(Av. 4) 142	Ilmenomagnetite (Ferrian ilmenite)	0.98	86.9	13.1	30.6	17.7	4.2	0.25	+67°
110-b, 244	Ilmenomagnetite (Ferrian ilmenite)	2.13	91.3	8.7	40.5	23.5	6.4	0.27	+63°
12(Av.6) 8a-9-12	Magnetite	2.40	97.1	2.9	48.7	28.15	4.1	0.14	+65°
Quartz-Oligoclase Granitic Gneiss									
135	Martite (Magnetite)	7.33	34.5	65.5	16.3	9.57	2.2	0.23	+83°
Pyroxene Granite Gneiss and Pyroxene Syenite Gneiss									
248	Ferrian ilmenite (Ilmenomagnetite)	1.27	24.4	75.6	4.6	2.7	4.9	1.82	-68°
124	Ilmenite Ilmenomagnetite	1.23	39.8	60.2	18	10.4	3.6	0.34	-33°
120	Ilmenite Ilmenomagnetite	6.68	36.4	63.6	15	8.7	8.2	0.94	-17°
132	Ilmenomagnetite Ferrian ilmenite	4.54	52.7	47.3	33	19.1	6.0	0.31	+77°
58	Ilmenomagnetite (Ferrian ilmenite)	1.52	83.6	16.4	36.6	21.2	5.4	0.25	+51°
Fayalite-Ferrohedenbergite Microperthite Granite									
124	Ferrian ilmenite (Ilmenomagnetite)	1.23	35	65	27	16	12.2	0.8	-69°
243	Ferrian ilmenite (Ilmenomagnetite)	1.02	37	62	20	11.6	3.0	0.3	-77°
Diorite Gneiss									
126	Ferrian ilmenite	4.28	----	100	3.2	1.86	1.93	1.04	-56°
129	Ferrian ilmenite Ilmenomagnetite	5.77	50.2	49.8	30.4	16.6	27.2	1.64	+2°
Anorthosite and Anorthosite Mortar Gneiss									
157[b]	Hemoilmenite Metailmenite (Ilmenomagnetite; ilmenohematite, rutile	0.64	18.8	81.2	0.86	0.50	0.80	1.6	-63°
					1.70	0.99	0.40	0.4	+61°
Granoblastic Gabbroic Anorthosite Gneiss									
156[b]	Hemoilmenite Metailmenite (Ilmenomagnetite; rutile)	0.80	25	75	0.54	0.26	0.81	3.1	-62°
					1.34	0.78	0.45	0.6	+52°
Gabbro or Gabbroic Gneiss (Anorthositic Series)									
83	Ilmenite	11.68	0.2	99.8	0.50	0.29	0.45	1.6	+69°
474,477 478	Ilmenomagnetite Ilmenite							2.1	+49°

a. Chemical data based on composite sample of 60 specimens; magnetic data on 5 samples with reverse and 8 with normal remanent magnetism.

b. Chemical data based on composite sample of 75 specimens; magnetic data on 8 samples with reverse and 4 with normal remanent magnetism.

I = Intensity of magnetization in cgs units.
H = Strength of magnetic field = 0.58 oersted for area involved.
I_R = Intensity of remanent magnetization
I_{MK} = Intensity of induced magnetization in earth's field. (Magnetic susceptibility x H)

* The term nonmagnetic oxides as used here refer to oxide concentrates separable magnetically from magnetite because of their low susceptibility. Actually these minerals may have considerable remanent magnetism.
() Brackets indicate mineral in subordinate amount.
- Data averaged where more than one sample.

Table 2a - Variation of magnetic properties with variation in mineralogy and lithology, Northwest Adirondacks

METASOMATIC AND CONTAMINATED GRANITIC GNEISSES

Field No. of Samples	Wt. % Oxide minerals in rock	Recalculated * non-magnetic oxides				Fe_2O_3 as % of total oxide minerals	* Non-magnetic oxides as % of total oxide minerals	Susceptibility in units of 10^{-3} per gram oxide minerals	Computed induced magnetization in units of 10^{-3} per gram (I_{HK})	Remanent magnetization in units of 10^{-3} per gram oxide minerals (I_R)	I_R/I_{HK}	Inclination of remanent magnetization
		% Total TiO_2	% Excess TiO_2	% FeO-TiO_2	% Fe_2O_3							
Pyroxene (or Hornblende) Quartz-Microcline Gneiss (± Plagioclase)												
(Granitized pyroxene-quartz-feldspar metasediments in contaminated microcline-rich granitic material)												
87,121	8.06	9.5	1.9	14.2	85.9	0	100	0.066	0.038	18	473	-65°
126	6.67	8.0	5.5	4.7	89.8	0	100	0.053	0.031	0.85	27	-70°
125	1.59	6.7	6.1	2.0	91.9	0	100	0.151	0.086	4.05	45.8	-69°
Sillimanitic Quartz-Microcline Gneiss												
(Granitized metasedimentary biotite quartz-plagioclase gneiss)												
21-4.11[A] 214	4.58	11.5	4.0	14.4	81.6	0	100	0.095	0.048	48.3	1006	-64°
136,137	8.58	12.0	10.8	2.3	86.9	0	100	0.110	0.065	21.5	338	-65°
97, 105	5.25	14.4	4.7	18.6	76.7	0	100	0.114	0.066	23.4	355	-65°
6,15,18, 27	4.86	16.8	7.9	16.2	76.3	0	100	0.122	0.070	97.0	1386	-69°
Clinopyroxene-Plagioclase Granulite												
123	5.35	27.0	5.4	40.5	54.1	1.7	98.5	2.18	1.260	50.0	40	-59°
Granitized Metasediment and Contaminated Granite Gneiss With Magnetite and Fe_2O_3 - FeO.TiO_2 - (TiO_2) Minerals												
88, 94	2.05	12.9	5.5	18.1	76.6	42.1	57.9	20.6	11.57	25.1	2.9	-55°
98, 103, 122	7.31	20.5	9.1	21.8	69.1	31.4	68.6	12.1	7.00	18.4	2.6	-51°
22, 139	4.16	21.2	9.7	21.3	69.5	69.5	30.5	37.5	21.7	7.3	0.34	+3°
99, 109	4.99	48.1	31.0	32.4	36.6	49.1	50.9	27.5	16.0	10.1	0.63	+3°
66,75,81 135a,135c 241,242	5.45	36.8	15.0	40.5	44.5	83.1	16.9	38.0	22.0	4.1	0.19	+67°

other but nevertheless may have been different to some extent. The susceptibility and remanent magnetization of the oxide minerals were determined by computation from the magnetic properties and the weight percent of the oxide minerals of the rock. Despite the possibilities for error just discussed, the systematic consistency of the data leads us to believe that they afford a good qualitative basis for discussion.

Induced Magnetization.—The value of the induced magnetization is the product of the earth's field and the magnetic susceptibility, a variable dependent primarily on the percent of magnetite in the rock and, in addition, on the nature and previous physiochemical history of the magnetite, and the size, shape, and mode of aggregation of the magnetite grains. The relationship of the susceptibility to the volume percent of magnetite in the rocks is shown in Figure 2. The scatter of values is undoubtedly related to some of the other factors mentioned, but it is apparent the magnetic susceptibility of a rock is primarily dependent upon the volume percent of magnetite. This relationship can be expressed most simply as $K = 2.6\,(V)^{1.33} \times 10^{-3}$ cgs where K is the magnetic susceptibility and V is the volume percent of the

Table 2b - Variation of magnetic properties with variation in mineralogy and lithology Northwest Adirondacks

Field No. of samples+	Minerals	Wt. % total oxide minerals in rock	Fe_3O_4 as % of total oxide minerals	*Non-magnetic oxides as % of total oxide minerals	Susceptibility in units of 10^{-3} per gram oxide minerals	Computed induced magnetization in units of 10^{-3} per gram (I_{HK})	Remanent magnetization in units of 10^{-3} per gram oxide minerals (I_R)	I_R/I_{HK}	Inclination of remanent magnetization
OXIDE CONCENTRATIONS									
Replacement Oxide Concentrations in Skarn									
16,17	Magnetite Clifton Mine	81.67	95.6	4.4	181	105.0	8.7	0.08	+ 45°
Replacement Oxide Concentrations in Migmatitic and Granitized Metasedimentary Gneiss, Benson Mines									
47	Magnetite	54.50	98.9	1.1	85.3	49.5	29.0	0.58	+ 65°
49	Magnetite	51.37	88.9	11.1	90.7	52.6	9.5	0.18	+ 59°
212	Magnetite (Titanhematite)	42.61	79.6	20.4			13.4		+ 21°
114	Magnetite Subtitanhematite	41.55	45.9	54.1	33.7	19.5	3.8	0.19	- 39° - 70° + 15°
112	Subtitanhematite (Magnetite)	38.74	27.4	72.6	5.7	3.3	10.9	3.27	
113	Subtitanhematite (Magnetite)	42.52	17.1	82.9	1.6	1.0	7.0	7.37	- 18°
115	Subtitanhematite	32.49	1.8	98.2	0.3	0.17	11.7	68.90	- 22°
48	Subtitanhematite	38.43		100.0	0.23	0.13	4.4	34.10	- 77°
Replacement Oxide Concentration in Sillimanitic Granitized Gneiss									
117	Hematite	44.70	0.2	99.8	0.85	0.49	0.17	0.35	+ 55°
Gneissic Oxide-Rich Segregation in Pyroxene Syenite Gneiss									
140	Ilmenomagnetite Ferrian ilmenite	17.96	48.1	51.9	36.6	21.2	14.3	0.67	+ 43°
Oxide Segregations Within Anorthosite Mass									
202	Ferrian ilmenite (Ilmenomagnetite)	21.70	16.6	83.4	0.84	0.49	0.14	0.28	+ 17°
85	Ilmenomagnetite	81.64	51.8	48.2	22.8	13.2	1.66	0.13	+ 31°

I = Intensity of magnetization n cgs units.
H = Strength of magnetic field = 0.58 oersted for area involved
I_R = Intensity of remanent magnetization
I_{HK} = Intensity of induced magnetization in earth's field (Magnetic susceptibility x H)

* The term nonmagnetic oxides as used here refer to oxide concentrates separable magnetically from magnetite because of their low susceptibility. Actually these minerals may have considerable remanent magnetism.
( ) Brackets indicate mineral in subordinate amount.
+ Data averaged where more than one sample.

magnetite. This expression holds only for values of V between 0.1 and 10. For lesser values, neither the chemical analyses nor the magnetic measurements are sufficiently accurate to be significant. We have not sufficient data to determine adequately the curve for values of V greater than 10 but it is probably similar to that derived by Werner (27).

Normal or Positive Remanent Magnetization.—Where magnetite forms more than 80 percent of the oxides and oxides are present as accessory minerals only, the remanent magnetization is 0.2–0.3 of the induced magnetization and is normally positive with an angle of inclination within 15° of present direction of the earth's field. The remanent magnetization in these specimens is added to the induced magnetization to give the total intensity of natural magnetization as the induced magnetization also is positive.

Reverse or Negative Remanent Magnetization.—Where intermediate mem-

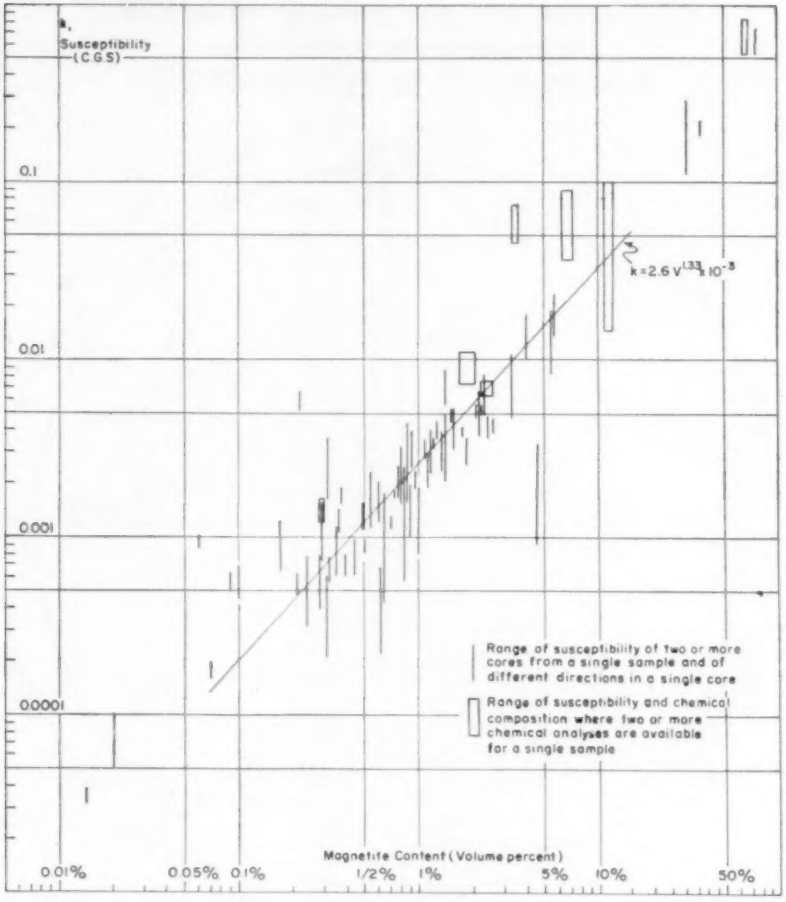


FIG. 2. Variation of magnetic susceptibility with magnetite content.

bers of the Fe_2O_3-FeO.TiO_2-(TiO_2) system constitute more than two-thirds of the total oxides, the remanent magnetization is negative, and in all specimens where they are the only oxides (20 examples) the angle of inclination is normally within 10° of the present angle of inclination of the earth's field but oriented with the south-seeking pole down in contrast to the normal orientation of north-seeking pole down in northern hemisphere.

The data show that nearly pure hematite and ilmenite have insignificant remanent magnetization; subtitanhematite and ferrian ilmenite have low to moderate values of remanent magnetization; and titanhematite, rutiloilmenohematite, and mixtures of hemoilmenite and ilmenohematite have high though

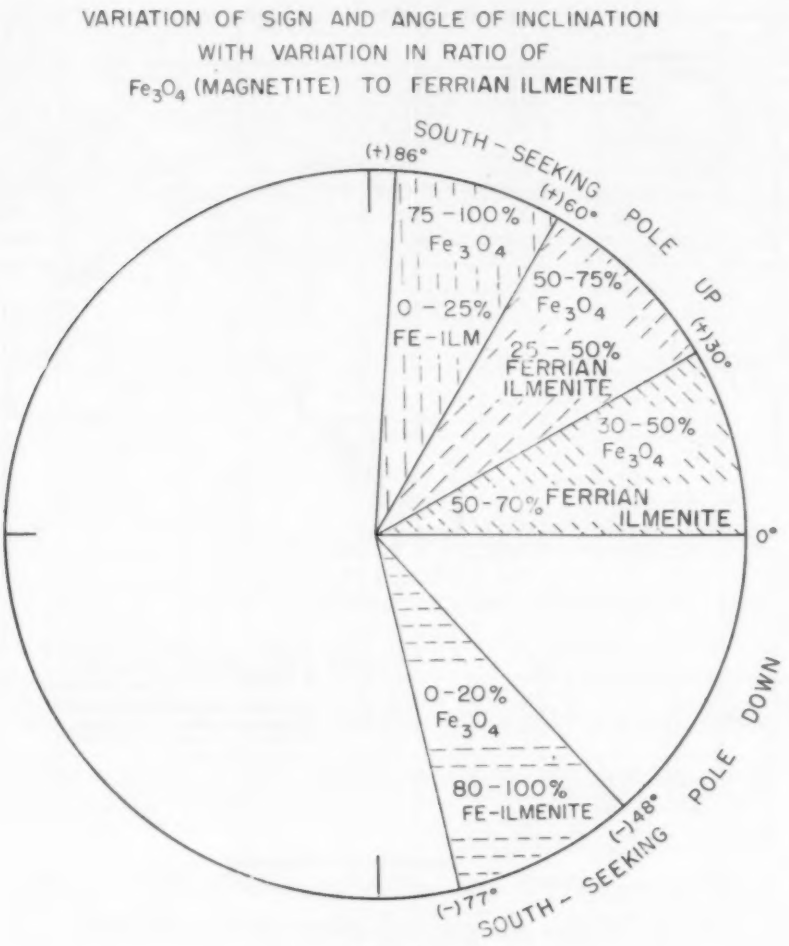


FIG. 3.

variable intensities of remanent magnetization. The ferrian ilmenite of amphibolite generally appears to have a lower intensity of remanent magnetism than that of the granites and granitic gneisses. A difference in physico-chemical history and retentivity may be involved.

The induced magnetization in the intermediate members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) series is so small that it does not appreciably affect the total magnetization.

Diverse Remanent Magnetization.—The magnetic properties of the rocks

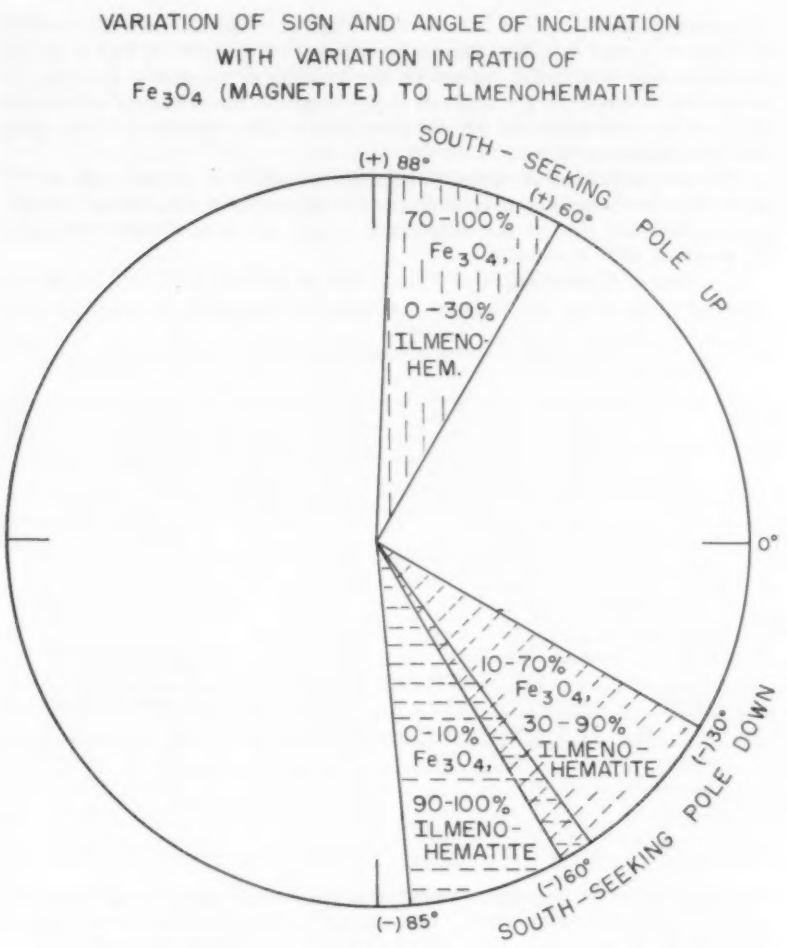


FIG. 4.

in which *both* magnetite and the magnetic iron-titanium oxide minerals occur are consistent with the hypothesis that the magnetite grains have a normal or positive remanent magnetization whereas the iron-titanium oxide minerals have reverse remanent magnetization. *Diverse* remanent magnetization thus exists within the rock and the remanent magnetization actually measured is a resultant.

Diverse remanent magnetization is best shown by the systematic manner of variation of the sign and angle of inclination for rocks in which there is an

increasing ratio of the Fe-Ti oxides to Fe_3O_4. The data are summarized in Figures 3 and 4. The chemically determined percent of Fe_3O_4 in the magnetite has been used instead of the percent of magnetite mineral. If reasonable assumptions are made as to the values of the remanent magnetization and its orientation in the different minerals the results are consistent with the experimental data.

The magnetization of rocks with mixed minerals is reverse only in the sense that the S-seeking pole is down, for the angle of inclination is intermediate between that of the different minerals and is not truly reverse in the sense of 180° reversal.

Anomalous Magnetization of Rocks.—All of the data presented so far are essentially consistent, but some of our samples (less than 10 percent) have

Table 3 - Variation of anomalous magnetic inclination for rocks with abnormally weak or abnormally strong remanent magnetization

Field No. of sample	Minerals	Wt. % total oxide minerals in rock	Fe_3O_4 as % of total oxide minerals	* Non-magnetic oxides as % of total oxide minerals	Susceptibility in units of 10^{-3} per gram oxide minerals	Computed induced magnetization in units of 10^{-3} per gram (I_{NR})	Remanent magnetization in units of 10^{-3} per gram oxide minerals (I_R)	I_R/I_{NR}	Inclination of magnetization
Biotite Quartz-Plagioclase Gneiss									
106	Ilmenohematite	3.77	0.5	99.5			11.45		- 31°
24	Ilmenohematite Hemoilmenite (Ilmenomagnetite)	9.24	5.8	94.2	15.5	9.0	18.5	2.06	- 13°
56B	Hemoilmenite Magnetite	6.11	25.7	74.3	25.3	14.7	7.12	0.48	+ 76°
Talcose Migmatitic Quartzite									
229	Rutileilmeno-hematite	2.83		100	0.066	0.04	2.24	56	+ 60°
Microperthite Granite Or Equivalent Gneiss									
211	Magnetite	2.56	95.8	4.2	51.7	30	25.4	0.85	- 50°
179	Ilmenomagnetite	1.16	88.0	12.0	41.3	23.9	28.4	1.18	- 58°
178	Ilmenomagnetite	1.76	+90		67.2	39	16.8	0.43	- 30°
187	Ilmenomagnetite	1.58	89.2	10.8			37.4		- 6 °

anomalous magnetic properties when compared with the prevailing values for rocks of equivalent composition. Data on such anomalous rocks are given in Table 3 and 4.

All the rocks with anomalous magnetic properties of Table 3 with one exception (No. 211) correlate with peculiarities of geology. Those with abnormally low remanent magnetization occur as thin layers of metasediment (Nos. 106, 24, 56-b, 229) within gneisses having magnetic properties normal for the Adirondack rocks. The two amphibolites of Table 4 (Nos. 209 and 130-b) also occur as thin layers within microcline-rich granitic gneiss having magnetic properties consistent with their mineralogy. The rocks (Nos. 178, 179 and 187) with abnormally high remanent magnetization and anomalous sign are local pyroxenic granite facies within normal hornblende granite.

Data on 13 specimens of amphibolite are available (Table 4). On the

basis of their mineralogical composition two (Nos. 55 and 72) have a consistent (+) inclination for the remanent magnetization, four (Nos. 52, 119, 311–194, 41) have a consistent (−) inclination and seven (Nos. 133, 73, 199, 200, 201, 130-b, 209–310) have a (+) remanent magnetization where a (−) might have been anticipated. All of the last have a member of the $FeO.TiO_2$-Fe_2O_3-(TiO_2) system as the dominant to exclusive mineral. The reason for about half of the amphibolites showing anomalous behavior is not apparent, though in part it may be due to instability of the original low reverse remanent magnetism.

Table 4 - Comparison of amphibolites with normal and anomalous magnetic properties

Field No. of samples	Minerals	Wt. total oxide minerals in rock	Fe_2O_3 as % of total oxide minerals	Nonmagnetic oxides as % of total oxide minerals	Susceptibility in units of 10^{-3} per gram oxide minerals	Computed induced magnetization in units of 10^{-3} per gram (I_{HK})	Remanent magnetization in units of 10^{-3} per gram oxide minerals (I_R)	I_R/I_{HK}	Inclination of magnetization
				Amphibolite					
55	Magnetite (Ferrian ilmenite)	14.12	71.0	29.0	31.1	18.0	7.19	0.25	+50°
72	Magnetite Ferrian ilmenite	16.17	41.0	58.9	33.2	19.3	3.0	0.16	+30°
133	Ferrian ilmenite Ilsenomagnetite	8.44	19.5	80.5	14.3	8.2	0.57	0.07	+25°
73	Ferrian ilmenite Ilsenomagnetite	2.42	14.9	85.1	9.1	5.3	4.4	0.83	+48°
199	Ferrian ilmenite	0.50		100.0			8.9		+28°
200	Ferrian ilmenite	7.60	6.4	93.6	4.6	2.64	3.55	1.34	+2°
52	Ferrian ilmenite	0.76		100	3.2	1.86	1.8	0.95	-9°
119	Ferrian ilmenite	2.84	9.6	91.4	4.5	2.59	1.4	0.57	-40°
41	Ferrian ilmenite	2.41		100	1.7	0.98	1.75	1.78	-59°
201	Ferrian ilmenite	2.54	2.8	97.2	1.8	1.05	0.45	0.42	+76°
311, 194	Ferrian ilmenite	7.04	2.8	97.2	2.2	1.28	4.1	3.20	-45°
209, 310	Hemoilmenite	2.55	8.1	91.9			0.90		+68°
130-b	Ilsenohematite Hemoilmenite	3.32	3.3	96.7	3.4	1.97	1.51	0.77	+81°

MAGNETIC ANOMALIES IN RELATION TO LITHOLOGY AND MINERALOGY

The magnetic anomaly of a homogeneous mass of material is produced by its total natural magnetization, the vector sum of its remanent magnetization (I_R) and its induced magnetization (I_{HK}). In the preceding section we have seen that the remanent magnetization is related to composition (and physicochemical history) of the oxide minerals and the induced magnetization primarily to the content of magnetite. Because the data in Tables 2, 2a, and 2b also show a relationship between the lithology and mineralogy the rocks we are able by combining these two types of information, to predict in a general way what magnetic anomaly one can expect from a given type of metamorphic or igneous rock in the Adirondacks.

The correlation of magnetic oxide minerals with lithology is summarized

FIG. 5. Variation of composition of iron-titanium oxide assemblages with variation in the nature of the rock, Adirondacks.

in Figures 5 and 6. Figure 5 shows that the composition of the disseminated oxides in *igneous* rocks lies almost wholly to the right of a vertical line through the Fe_3O_4 apex, that is, that they contain mixtures of titaniferous magnetite and ferrian ilmenite or hemoilmenite. The composition of the disseminated oxides in metasediments, migmatites, and gneisses of granitization together with the replacement ores lies almost wholly to the left of this line, showing that they generally contain mixtures of magnetite and titaniferous hematite though locally magnetite only. The compositions of the oxides in potassium-rich granite and in the rocks of metasedimentary derivation alone overlap.

The compositions of the oxide segregations in igneous rocks and of replacement vein oxide deposits as shown by Figure 6 similarly overlap only to a very slight degree. The composition of some oxide aggregates occurring

as small late stage knots and lenses in granite pegmatite or alaskite alone have compositions similar to those of local magnetite replacement ores. A discussion of the significance of the composition of the ilmenomagnetite for the magmatic origin of ilmenomagnetite-ilmenite deposits has been given by Buddington, Fahey and Vlisidis (8, 9).

The correlation of aeromagnetic anomalies, mineralogy, and lithology is shown in Table 5. The aeromagnetic intensities shown in this table were determined from surveys made at about 1,000 feet above ground and the values in gammas are relative to an arbitrary datum. The results of the survey of 27 quadrangles have shown that in the area under discussion the

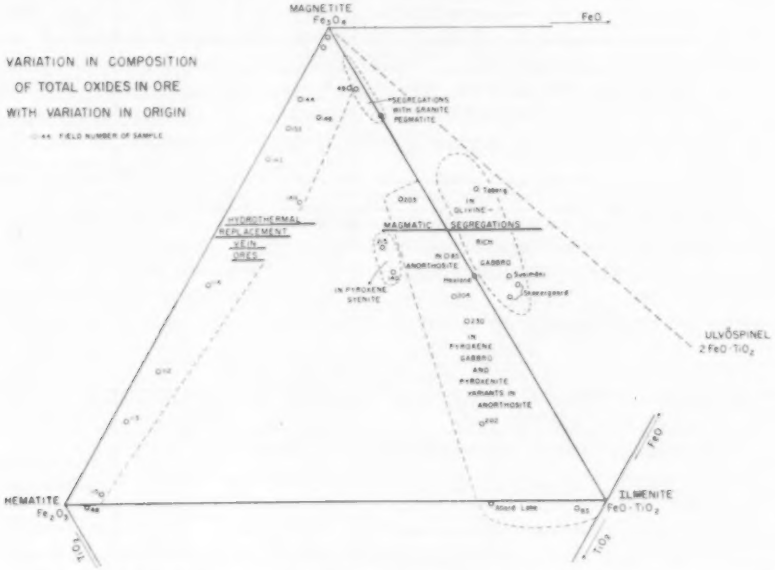


FIG. 6. Variation of composition iron-titanium oxide assemblages in ore with variation in origin, Adirondacks. Oxides of ores from several other localities added for comparison.

background magnetic field, that is, the magnetic field of the earth undisturbed by local geologic features, is about 5,000 gammas so that anomalies can be considered positive or negative depending upon whether they are above or below this figure. An attempt was made in preparing this table to choose only regional anomalies so that the magnetic effects of edges and other structural features would be eliminated—in particular, the negative anomalies are chosen to eliminate the possibility that they might be due to lightning or artificial causes.

The green pyroxene syenite gneiss and green pyroxene granite gneiss are characterized by accessory oxides whose composition may be computed in

Table 5 - Correlation of regional aeromagnetic anomalies with mineralogy and lithology

Rock and locality	Aeromagnetic Intensities*		Wt.% Fe_3O_4	Wt.% oxides of system Fe_2O_3-FeO.TiO_2-(TiO_2)	Nonmagnetic minerals+ of Fe_2O_3 · FeO.TiO_2 (TiO_2) system
	Minima	Maxima			
Intense Negative Magnetic Anomalies					
Pyroxenic microcline-rich granitic gneiss, 1.5 miles N of East Pond, (Rose Pond area) Big Moose Q	3400-4200		0	8.6	Titanhematite or Rutilcilmenohematite
Migmatitic hornblendic and pyroxenic plagioclase-bearing microcline granitic gneiss, southwest of Hellgate Ponds, McKeever quad.	3470		0	8.1	Titanhematite or Ilmenohematite
Sillimanitic and/or biotitic microcline-rich granitic gneiss, South Russell belt, Russell quad.	3360-4500		0	5.2	Rutilcilmeno-hematite
Mild Negative Magnetic Anomalies					
Amphibolite, 2 miles SE of St. Regis, Nicholville quad.	4740		0	A little	Ferrian ilmenite
Hornblende granite, Stark Falls and Parmeter Pond belts, Stark quad.	4390-5040		0.18	0.69	Ferrian ilmenite
Pyroxene syenite gneiss, 0.3 mile SW of Childwold Station, Childwold quad.	4760-4850		0.1	0.4	Ferrian ilmenite
Nearly Neutral					
Hornblende microperthite granite, Bryants Bridge, Oswegatchie quad.	5000		0.2	0.4	Ferrian ilmenite
Hornblende microperthite granite, W. of Briggs, Oswegatchie quad.	4900 -	5050	0.37	0.7	Ferrian ilmenite
Pyroxene syenite gneiss, 1.5 to 3.3 miles SSW of Childwold Station, Childwold quad.	5000 -	5050	1.00	1.2	Ferrian ilmenite
Sillimanitic quartz-microcline granitic gneiss, about one mile S of Sellecks Corners, Stark quad.	5025		1.2	2.9	Ilmenohematite (Hetailmenite) (Martite)
Positive Magnetic Anomalies					
Hornblende microperthite granite and alaskite, 0.4 to one mile W of Strifts School, Lowville quad.	5150	5225	0.76	0.35	Ferrian ilmenite
Hornblende granite gneiss, 1.5 miles W of Cold Brook School, Stark quad.		5400-5500	1.5	0.5	Ferrian ilmenite
Sillimanitic microcline granitic gneiss, near Lyonsdale, Port Leyden quad.		5700	3.4	1.1	Ilmenohematite (Metailmenite)
Hornblende microcline-oligoclase granite gneiss with sphene; Stone School, Russell quad.		5800	2.3	0.1	
Positive Magnetic Anomalies					
Hornblende microcline-oligoclase granite gneiss, with schliere of amphibolite, 1.25 mile SW of W end of Utowana Lake, Raquette Lake quad.		6300	4.2	2.1	Hemoilmenite (Ilmenohematite)
Hornblende microcline-oligoclase granite gneiss with sphene; 0.8 miles SSE of Catherineville School, Potsdam quad.		6400	3.9	0.8	Martite (Ferrian ilmenite)
Hornblende microcline-rich granitic gneiss with lenses and schliere of amphibolite, 1.5 miles E of Sevey road junction, Childwold quad.		6500	4.3	1.6	Hemoilmenite (Ilmenohematite)
Microcline granite gneiss, subordinate plagioclase, meagre sphene and hornblende, just N of village of Black Brook, Ausable quad.		7380	5.1	0.8	Ferrian ilmenite Hemoilmenite
Exceptional Anomalies					
Potassium-rich hornblende microperthitic microcline granitic gneiss, S. & W. of Kildare, Childwold quad	4375-4880		2.2	1.7	Ferrian ilmenite (Hemoilmenite) (Ilmenohematite)
Microcline granitic gneiss, south along outlet of Twitchell Lake, Big Moose quad.		5700	1.3	0.7	Ilmenohematite
Pyroxene syenite gneiss, 1.75 miles ENE of Texas road school, Lowville quad.		6300	2.5	2.8	Ferrian ilmenite

terms of magnetite and ilmenite. Ilmenite may occur in part in exsolution intergrowths in the magnetite. The accompanying ilmenite may be either ferrian ilmenite or ilmenite. A slight amount of pyrrhotite may be present. The pyroxene of part of these gneisses is predominantly an orthopyroxene rich in FeO, a ferrohypersthene or eulite. Almandite is often present as a product of metamorphic reconstitution and the rocks may be regarded as a charnockitic facies. Local facies of these gneisses have ferrian ilmenite as the predominant to almost exclusive oxide mineral, in which case they give rise to a slight negative anomaly. Otherwise they give a low to high positive magnetic anomaly depending on the percent of ilmenomagnetite present. One belt of pyroxene syenite gneiss gives rise to a ridge of positive aeromagnetic anomaly with peaks of 1,100 to 1,500 gammas above normal.

A small belt of green fayalite ferrohedenbergite microperthite granite occurs in the Cranberry Lake quadrangle. The rock uniformly has ferrian ilmenite predominant over ilmenomagnetite and a concomitant reverse remanent magnetism. In the earth's field however the rock has a sufficient amount of induced magnetism so that it gives a neutral to low positive (100–200 gammas) aeromagnetic anomaly.

The magnetite of the red hornblende microperthite granite is an ilmenomagnetite with 6 to 8 percent Fe_2O_3 in solid solution and 10 to 13 percent $FeO.TiO_2$ largely as exsolved ilmenite microintergrowths. The magnetite of the equivalent hornblende microcline-oligoclase gneisses which were formed at lower temperatures than the granite has only 1.1 to 7.5 percent $FeO.TiO_2$, largely as exsolved microintergrowth except in the magnetite with less than two percent ilmenite where it may be in solid solution. In part of the granite gneiss the ilmenite has reacted to yield sphene and a more iron-rich hornblende, and magnetite alone remains. The percent of Fe_2O_3 in solid solution in the magnetite of the gneisses is also less than in that of the granite, and varies from 0.5 to 5.5. Both ilmenomagnetite and ferrian ilmenite are generally present in the microperthite granite but the ratio of one to the other varies widely and in some extensive areas ferrian ilmenite is the predominant to exclusive oxide. The granite with magnetite slightly greater or slightly less than ferrian ilmenite yields a neutral to slight positive magnetic anomaly (0 to + 300 gammas), but the belts of granite with ferrian ilmenite the predominant oxide mineral give a mild negative anomaly (0 to 500 gammas below normal).

Facies of any of the granites or granite gneisses that are contaminated with metasedimentary material or especially with amphibolite may have as much as several percent of magnetite and give rise to broad belts of high posi-

* Gamma values at 1,000 feet above ground and relative to an arbitrary datum. The total intensity of earth's field increases about 500 gammas from the SE corner of Raquette Lake quadrangle to NW corner of Potsdam quadrangle so that values for northern quadrangles are slightly higher.

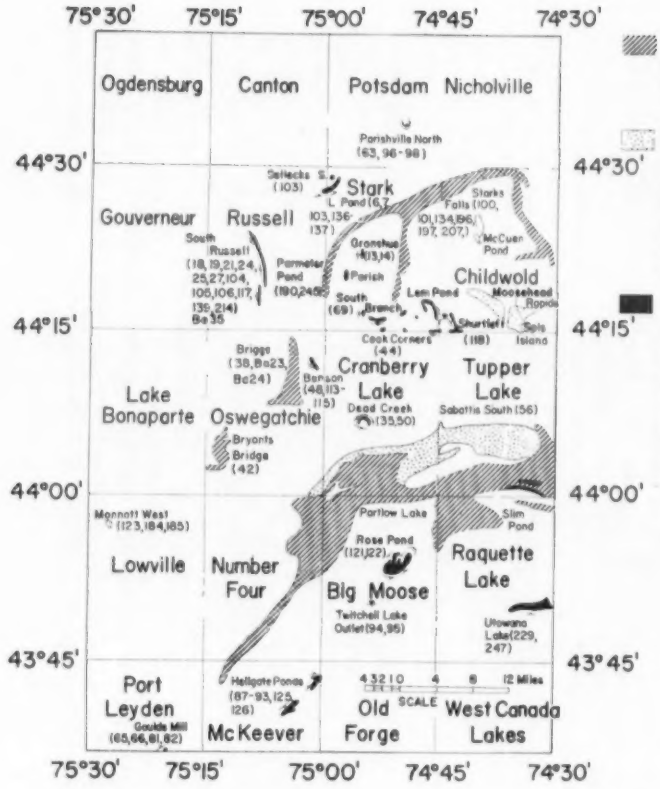
† $FeO.TiO_2$ and Fe_2O_3 as intergrowths or in solid solution in magnetite have been calculated with the nonmagnetic oxides. The percentages of the oxides are based on chemical analytical data on grab samples that can therefore only be considered as controlled estimates. The term nonmagnetic oxides as used here refers to oxide concentrates separable magnetically from magnetite because of low susceptibility. Actually these minerals may have considerable remanent magnetization.

tive magnetic anomaly (1,000 to 1,500 gammas above normal). Indeed if one had to guess at the interpretation of a long broad belt of positive aeromagnetic anomaly in the Adirondacks without opportunity to investigate it, an hypothesis that it was due to contaminated granite or granite gneiss would be more probable than that it was due to mafic rocks.

One kind of gneiss underlying extensive areas in the northwest Adirondacks is a sillimanitic quartz-microcline gneiss with biotite or muscovite and disseminated oxide minerals, locally with garnet, interpreted as a granitized biotite quartz plagioclase gneiss. The oxides in part of it are exclusively titanhematite, ilmenohematite, rutiloilmenohematite, or rutilohematite, and in part of it the iron-titanium oxides are accompanied by magnetite. The iron-titanium oxides were formed at the same time as the magnetite. At a late stage in the development of the oxides, part of the magnetite has locally been in part hydrothermally oxidized to martite. Microcline-rich pyroxene gneisses may also carry titanhematite or ilmenohematite as the exclusive or predominant oxide. The other types of metasedimentary and metasomatic gneisses have not been carefully studied. The few samples observed have similar ranges and kinds of oxides as the quartz-microcline gneisses. The sillimanitic and pyroxenic quartz-microcline gneisses may give rise to belts of positive magnetic anomalies (often 500–800 gammas above normal), neutral areas, or intense negative anomalies (500 to 1,600 gammas below normal) depending on the ratio of magnetite to the iron-titanium oxides, which in turn depends on the degree of oxidation of the iron. Locally hornblendic quartz-microcline gneisses with several percent of magnetite give rise to belts of positive magnetic anomaly with peaks as high as 2,300 gammas above normal. Locally the gneisses have been modified by the introduction in quantity of magnetite or rarely subtitanhematite concentrations.

Aeromagnetic maps are available for only small areas of the anorthositic rocks. They show slight negative to neutral aeromagnetic anomalies with local low positive magnetic anomalies. The predominant to almost exclusive mineral in the coarse anorthosite with massive to mortar or porphyroclastic gneiss structure is hemoilmenite which in most samples is slightly to almost wholly altered to metailmenite. Ilmenomagnetite is a minor part of the oxides. The majority of the samples have a normal remanent magnetism. Samples of granoblastic gabbroic anorthosite gneiss from the Willsboro quadrangle have the same oxides as the anorthosites, but the majority have reverse remanent magnetism. The interpretation of the sign of the orientation of the remanent magnetism in these rocks is confused by the amount of metailmenite present and the commonly meager amount of oxides. The metailmenite appears to be of hydrothermal origin and post-major metamorphism. It occurs in rock of fresh road cuts and with accessory pyrite. Local anorthositic gabbro to gabbro facies of the anorthositic series have more oxides. The latter are ilmenomagnetite and ilmenite with the former in excess of the latter. Such rock has a normal remanent magnetism.

There are roughly 17 synclinal masses of metasediment and migmatitic facies in the northwest Adirondacks that are in substantial part reflected as negative anomalies in the aeromagnetic maps. We find that titanhematite,



AREAS OF NEGATIVE ANOMALY, N.W. ADIRONDACKS

Areas of mild negative anomaly (0 to (-) 500 gammas) underlain by hornblende granite or equivalent gneiss with ferrian ilmenite the nearly exclusive or predominant ferromagnetic oxide. Total ferromagnetic oxides predominantly 0.3 to 1.1 percent.

Areas of mild negative anomaly (0 to (-) 500 gammas) underlain by synclinal belts of metasedimentary rocks, largely partly granitized or with granitic or pegmatitic layers. Ferromagnetic oxides consist of magnetite plus ilmenohematite and/or hemoilmenite. Effects of ilmenohematite and/or hemoilmenite are strongest. Total ferromagnetic oxides predominantly 3 to 6 percent.

Areas of intense negative anomaly (minima of (-) 400 to (-) 1640 gammas) underlain by synclinal belts (in part overturned isoclinal) of metasediments, in large part granitized to yield microcline-rich quartz feldspar gneisses, often with sillimanite. Ferromagnetic oxides are exclusively or predominantly ilmenohematite, rutilohematite, rutiloilmenohematite or titanhematite. Total ferromagnetic oxides predominantly between 3 to 6 percent.

Numbers refer to analyzed samples

FIG. 7.

ilmenohematite, rutiloilmenohematite, or rutilohematite is present in sufficient quantity in the rocks to account for the negative anomaly of eleven of the synclines (shown on Fig. 7); the bedrock beneath three of the areas is covered by drift and we do not have adequate data for the other three. For all the negative anomalies with minima of less than 4,300, the oxide mineral is commonly exclusively one or more of the iron-titanium minerals cited, as in the belt south of South Russell (Fig. 8).

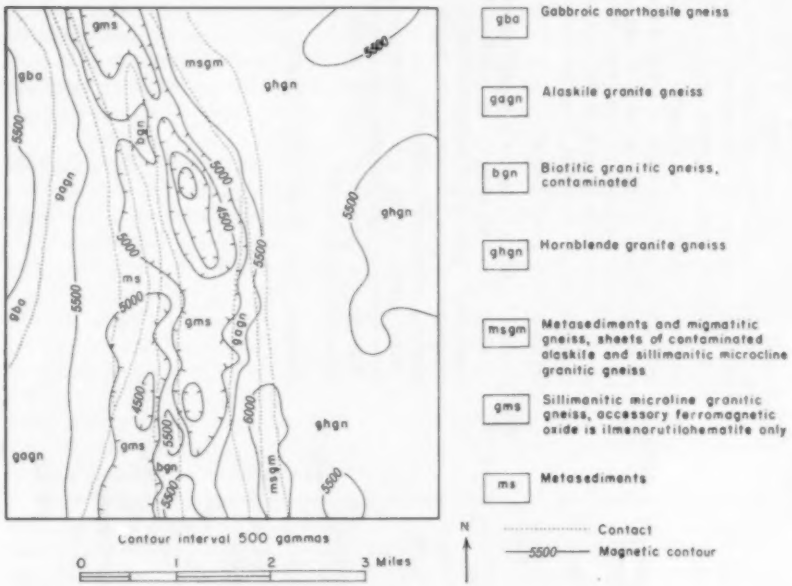


FIG. 8. Aeromagnetic map of part of Russell quadrangle, N. Y.

The local high positive anomaly (6450) southwest of Starks Falls within an area of negative anomaly is underlain by a skarn deposit of magnetite ore.

The oxides of the mafic rocks may show a very marked change on metamorphism. The primary gabbro normally has ilmenomagnetite and ferrian ilmenite or ilmenite. On thorough reconstitution to hornblende-andesine amphibolite with or without garnet, the magnetite may be wholly taken up by the hornblende and only ferrian ilmenite or occasionally hemoilmenite remain. The mafic rocks such as the olivine and pyroxenic gabbro and their metamorphosed pyroxene-garnet granulite equivalents may give a low to moderate positive magnetic anomaly whereas their hornblende amphibolite equivalents may yield a slight negative magnetic anomaly if thoroughly reconstituted or a high positive magnetic anomaly if magnetite has been introduced by solutions from accompanying granitic materials.

Subtitanhematite (about 1.5 to 2.5 percent TiO_2) occurs exclusively in replacement ore, alone or with magnetite, as at Benson Mines (15), where it is being mined on a large scale; as a subordinate mineral in local ore lenses at the Parish deposit, and locally as a minor mineral in other vein deposits. The subtitanhematite where alone or predominant gives a negative magnetic anomaly.

One major result of our work is to show that the ratio of ferrian ilmenite to magnetite is so highly variable in all of the Adirondack granites or granitic orthogneisses and in the orthopyroxene syenite gneisses (Table 2) that either a negative, neutral, or positive anomaly may result depending on whether ferrian ilmenite is predominant, about equal, or minor relative to magnetite. Similarly in granitic gneisses of metasomatic origin, the gneiss may give a negative, neutral, or positive anomaly depending on the ratio of titaniferous hematite to magnetite.

It is apparent in Table 5 that the negative effect of minerals of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) system must be taken into account in evaluating the order of magnitude of the positive anomaly which a given amount of Fe_3O_4, as magnetite, may be expected to produce. The data also show the results of differences in the intensity of negative magnetization which different members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) system possess and consequently the different amount they may reduce the positive anomaly expected from a given quantity of magnetite.

The positive aeromagnetic anomalies over rocks with magnetite the exclusive or predominant oxide are due wholly or almost wholly to the magnetism induced by the present earth's field whereas the negative aeromagnetic anomalies over rock with intermediate members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) system the exclusive or predominant oxide are due wholly or almost wholly to the reverse remanent magnetism.

As is to be expected, we find a number of exceptional anomalies that do not correspond to what would be expected from the oxides of the underlying rocks. The less than normal values for the mild anomaly of the area south and west of Kildare (Childwold quadrangle) are puzzling. Samples of what appears to be the predominant rock all have positive remanent magnetism though the angle of inclination is abnormally low. So much of this area is obscured by drift that the proper interpretation is in doubt. The anomaly south of Twitchell Lake (Big Moose quadrangle) is abnormally high for the composition of the oxides. The belt is only 0.25 mile wide, however, and the anomaly is probably affected by a belt of adjoining rock on the north with higher content of magnetite. The pyroxene syenite gneiss ENE of Texas school (Lowville quadrangle) also gives an abnormally high anomaly. The rock here is on the core of an anticline and there is reason to believe that gneiss with a higher percent of magnetite lies not far below the surface.

THE ORIGIN OF REVERSE REMANENT MAGNETIZATION

There are at present two major hypotheses to explain reverse remanent magnetization and each has much evidence to support it, though for different

examples. One hypothesis assumes that the earth's magnetic field is essentially stable over periods of hundreds of thousands of years but may periodically reverse itself about 180° in a relatively short time, a few thousand or few tens of thousands of years. The other hypothesis assumes that certain minerals or mineral assemblages have the inherent capacity for developing a reversed orientation under the appropriate conditions in the earth's field. The two hypotheses may be referred to as "periodic reversal" and "self-reversal." Both hypotheses must assume stability or at least substantial stability of the magnetization since the material cooled below the Curie point and the range of temperature within which the remanent magnetism developed, a period of perhaps hundreds of millions of years for the Adirondacks.

The permanent magnetization of many lava flows of Recent age has been studied and in practically all the orientation is in the direction of the earth's local magnetic field (13). Evidence from Recent sediments is also consistent with this. Hence, the hypothesis has been drawn that where rocks have *reverse* orientation of their remanent magnetization the permanent magnetization may have been acquired during a period when the north and south poles of the earth's field were reversed. A very large amount of data which is consistent with this hypothesis (25) has been accumulated in the last decade on Tertiary and older rocks.

The potential capacity of certain oxide minerals in rocks for self-reversal on cooling through a temperature interval below the Curie Point has, however, been experimentally demonstrated by Nagata (16, p. 245–247; 18b, p. 850–852) and Uyeda (26) for a ferric iron-rich ilmenite of dacite that has a natural reverse remanent magnetization, and by Kawai, Kume, Sasajima (14, p. 588–592; 864–868) for magnetite of the series Fe_3O_4-$2FeO.TiO_2$ in an andesitic tuff, which also has a natural reverse remanent magnetization. One specimen from the Adirondacks has demonstrated this characteristic in one heating and cooling cycle. Néel (20) has given the theoretical basis for several relationships in which *self-reversal* might occur. Nagata et al. (19) have further concluded as a result of experimental studies on minerals of the FeO-Fe_2O_3-TiO_2 system that where two ferromagnetic minerals coexist within a grain in the state of finely laminated structures, magnetic interaction occurs, is negative, and gives rise to reverse remanent magnetism.

We have previously proposed the hypothesis (4, 2) on the basis of interpretation of the natural phenomena that the magnetic members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) system have the property of self-reversal under the appropriate physiochemical conditions and that these minerals in the Adirondacks have thus acquired their negative remanent magnetization. The minerals and their physicochemical history are thus major factors in interpreting the origin and character of the remanent magnetism.

Runcorn (25, p. 278–279) has suggested the possibility that in the Adirondack rocks the remanent magnetization of both the magnetite and the ferromagnetic iron-titanium oxide minerals acquired a remanent magnetization at a period when the earth's field was reversed and both minerals thus originally had a reversed orientation of their magnetization. He proposed that during subsequent history the ferromagnetic iron-titanium oxide minerals were stable

and retained their reversed orientation but the magnetite was unstable, lost its original negative remanent magnetization, and has taken on a positive remanent magnetization approaching or approximating that appropriate to the present earth's field. The phenomena seem to us too complex to be satisfactorily explained by this simple hypothesis.

We have also found that the azimuths of the remanent magnetization for rocks with magnetite the major or exclusive magnetic mineral in one large belt of gneiss are concentrated in one sector of 55° and have an average azimuth of 324° and an inclination of 50°, or approximately 26° from the present earth's field (3). By contrast the azimuths of the remanent magnetization of rocks in the same belt with titaniferous hematite predominant or exclusive are almost wholly in different sectors from that of the magnetite and are neither in the same sector as that of the magnetite, or in the sector at 180° to that of the magnetite. These data indicate stability for both types of mineral.

The phenomena of magnetostriction at time of development and mineral orientation may be involved in the orientation of the remanent magnetism of some gneisses (12).

At an estimate the igneous rocks crystallized above 650° C, the gneisses between 650°–450° C and the granitized and metasomatic gneisses down to perhaps as low as 400° C. It is possible, however that 500° C is the lower limit for any of the rocks.

The Curie point (17, p. 30) for magnetite is 578° C, for hematite 675° C, for titanhematite about 565° C, for ilmenite (1) less than 100° C and is at intermediate temperatures for titaniferous magnetite with $FeO.TiO_2$ in solid solution and hematite or ilmenite each with the other in solution. Part of the remanent magnetism of the intergrowths may be acquired during the temperature range of exsolution. To have all these minerals acquire a negative remanent magnetization during a period of reversed earth's field would necessitate a very long time for the latter, since the isotherm for the different Curie points would be expected to be reached successively, primarily on cooling in consequence of erosion. This would mean removal of 6–10 miles of thickness of rock.

The problem, however, is present as to whether the empirical relationships found to hold for the northwest Adirondack gneisses are of local or general significance.

There is also the problem of how extensively developed in rocks are members of the Fe_2O_3-$FeO.TiO_2$-(TiO_2) system. Titaniferous hematite may be only local but there is a possibility that ferrian ilmenite, in at least small amounts, is a widespread accessory mineral. It may be re-emphasized here that there are large areas of granite in the Adirondack area with accessory ferrian ilmenite as the predominant oxide mineral that give small negative magnetic anomalies and have reverse remanent magnetism.

Six samples taken from oxide concentrations in the Edison belt, New Jersey, have magnetite by far the predominant oxide. The angle of inclination, however, is gentle to flat, where an angle of 73° might be expected. All of these specimens, however, have accessory grains consisting of a lamellar

intergrowth of magnetite with hemoilmenite, ilmenohematite, or rutile. This implies that these samples have had a different physicochemical history from the Adirondack rocks where this kind of intergrowth does not occur. We have determined the remanent magnetism in the hemoilmenite of the Allard Lake, Quebec, ore deposit and of a hemoilmenite-rich rock layer at Hibernia Pond, New Jersey, and found it to be reversed.

Graham (11) has proposed the possibility that reverse magnetic orientation may develop under certain circumstances and geologic history through the formation of one mineral in place after another, as in the case of maghemite after magnetite in certain Michigan diabase dikes. This cannot be the whole story, however, for we find that in these dikes where the oxide minerals consist of ilmenomagnetite and ilmenite with 40.9 percent Fe_3O_4 and 56.3 percent $FeO.TiO_2$ and only 2.8 percent maghemite, the rock also has reverse remanent magnetization. In part of the Adirondack rocks both partly martitized magnetite grains and separate ilmenohematite grains occur as dissemination in the same rock but the martite does not carry exsolved ilmenite and must have developed at a later stage and lower temperature than the ilmenohematite. We have no evidence that any of the titaniferous hematite minerals developed effectively through pseudomorphism of magnetite.

If the hypothesis of periodic reversal of the earth's field is true, then somewhere, and at many times, iron-titanium oxide minerals may have formed in rocks or ores during a period of normal orientation of the earth's field, and thereby have acquired and maintained a positive remanent magnetization, and should now be available for study in outcrops. Geologists could contribute to the solution of this problem if they would report the orientation of the *remanent* magnetization in all plutonic rocks or ores in which intermediate members of the system Fe_2O_3-$Fe.TiO_2$-(TiO_2) are present as the exclusive or predominant oxides.

In the light of the several possible explanations for the self-reversal of natural rocks, particularly those containing titaniferous hematite, one cannot at this time categorically state that the reversed magnetization of a rock has been produced by a reversed field of the earth.

U. S. Geological Survey,
Washington, D. C.
Princeton University,
Princeton, N. J.,
Jan. 3, 1958

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Economic Geology
Vol. 53, 1958, pp. 806–822

RELATIONSHIP OF ORE TO PORPHYRY IN THE BASIN AND RANGE PROVINCE, U.S.A.[1]

BRONSON STRINGHAM

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ABSTRACT

Data obtained during recent detailed mapping of intrusive areas in the eastern Great Basin combined with an examination and review of 107 mining districts in the Basin and Range Province of the United States containing hydrothermal deposits of Au, Ag, Pb, Zn, Cu, Mo, W, Hg, and U has led to the recognition of significant differences between "productive" intrusives, (those associated with hydrothermal mineralization) and "barren" intrusives, (without significant mineralization). For 86 percent of the deposits of Cretaceous and younger age there is a significant amount of associated intrusive porphyry or aphanitic rock present as large dikes, sills, and breccias with aphanitic matrix or more commonly as stocks or pipes occurring with or without granitoid textured rock. These rock types with few exceptions, are exposed within 2 miles of the ore deposit. The great majority of barren intrusives are of granitoid rocks only, except for the presence of smaller porphyry dikes and sills. Deposits of tungsten show an association preference with granitoid intrusives. These statistics indicate that in finding or developing a new ore deposit of the above metals other than tungsten, it is necessary to have a large intrusive aphanite porphyry existing within 2 miles of the exploration area in order reasonably to expect (for 86% of the cases) the existence of a significant ore body. Because barren intrusive porphyries do exist in the Basin and Range Province, further investigation of the differences and similarities between productive and barren porphyry plutons is contemplated.

[1] Assistance has been received from the University Research Fund and the Kennecott Research Fund, University of Utah.

INTRODUCTION

It has long been recognized that there is a close spatial association of sizable hydrothermal ore deposits and plutonic rocks. It is also well known that a great many plutons exist that are devoid of affiliated ore deposits. In the pursuit of new clues to aid the search for ore, a program of investigation was undertaken to determine if there are noticable differences between the "barren" and the "productive" plutons. A worldwide investigation of this sort is, of course, impractical. Accordingly, the territory within the Basin and Range Province of the United States as outlined by Fenneman (7) was selected as a sample area. Those acquainted with the province will recognize the many advantages inherent to it which make it an excellent place to conduct such a study.

The region as a whole is readiy accessible and many known hydrothermal ore bodies associated with intrusives are known. Also existing in the area is a very large number of barren plutons. Most of the plutons, barren and productive, are of Cretaceous and younger age and their development has in most places been subsequent to Nevadan and Laramide tectonic activity. Except for changes due to weathering, these younger plutons and the associated ore deposits, therefore, exist approximately in their original state thus proffering the minimum of superposed mineralogical and geological changes. The entire province is still a very fertile field for ore exploration. One obvious disadvantage is that over half of the area is overlain by recent Tertiary sediments and volcanic rocks that obscure large areas of the bed rock. This should not, however, seriously affect the statistics of occurrence.

SOURCES OF INFORMATION

Literature.—The geology of most of the mining districts within the Basin and Range Province is known at least with varying degrees of reliability through publications. As a rule, the larger the district, the more abundant and more nearly complete the geological accounts. Thus, the productive plutons within the mining districts have been fairly well described geologically. On the other hand good detailed descriptions of the barren plutons are few. The geographic position and general rock type of most of them is known but this information, though extremely helpful, is not complete enough to make basic comparisons.

Field Work.—In view of these facts it was decided to investigate some of the less known plutonic areas of the eastern Great Basin mapping in detail the petrology within the mass, as well as its periphery and adjacent wall rocks for geological setting. Accordingly, during the past two years, nine plutons have been studied and mapped under the writer's direction with the financial aid of University of Utah research grants, but reports on these areas have not yet been published in full.

1. Northern Pilot Range, Utah, Nevada
2. Kinsley, Antelope Range, east central Nevada (21)
3. Whitehorse, southern Toana Range, Nevada (1)
4. Cherry creek, Egan Range, Nevada

5. Egan Canyon, Egan Range, Nevada
6. Steptoe, Egan Range, Nevada
7. Swalls Mtn., northwest of Elko, Nevada.
8. Cortez Mtn., southeast of Beowawe, Nevada
9. East Shell Creek, Shell Creek Range, Nevada

Also during the past 2 years 13 additional plutons have come under surveillance through University of Utah thesis field studies. Each of these has been observed in some detail by the author.

1. Grouse Creek Range, northwestern Utah (W. H. Baker, unfinished thesis)
2. Newfoundland Range, northern Utah (15)
3. North Silver Islet Range, western Utah (2)
4. South Silver Islet Range, western Utah (2)
5. North Mineral Range, central Utah (13)
6, 7. South Mineral Range, central Utah (5)
8, 9, 10. Three separate but adjacent plutons, north Toana Range, eastern, Nevada (James D. Stephens, unfinished thesis)
11. Delno, northeastern Nevada (Donald R. Olson, unfinished thesis)
12. Sheeprock Range, north central Utah (4)
13. West Tintic, north central Utah (4)

To obtain a firmer basis for comparison of the productive and barren plutons, the writer has also observed the surface geology of 95 of the 107 mining districts in the Basin and Range Province, having deposits believed to be hydrothermal in origin and which individually have produced over $3,000,000 of gold, silver, copper, lead, zinc, mercury, molybdenum, tungsten, and uranium. Park City, Little Cottonwood and Marysvale, three of the larger mining districts, though strictly outside the well-established border of the Basin and Range, are in such proximity that they are included.

COMPARISON OF PRODUCTIVE AND BARREN PLUTONS

As a result of this systematic study of the numerous plutons there has emerged considerable differences between those associated with economic mineralization and barren ones.

Based upon a count of the Cretaceous and younger plutons shown on geologic maps of the several states within the Basin and Range Province, together with personal knowledge of Utah and Eastern Nevada and a geologic map of Nevada compiled by Stephenson (20) it is estimated that 350 to 400 barren granitoid plutons exist within the area.[1]

As far as is known they are for the most part of intermediate to acid composition and, except for smaller porphyry dikes and sills, are largely granitoid in texture. From the studies of the mining districts it is shown that 59 Cretaceous and younger granitoid plutons are associated with economic mineral deposits of the same age.

Conversely, in an overwhelming majority of the productive mining dis-

[1] These figures are probably low as each new detailed study (8, 18, for example) commonly reveals more distinct and separate intrusives than are illustrated for the same area on the generalized state geologic maps. Further inference of the conservative nature of these figures is suggested by Knopf's (11, 12) earlier works and more firmly by the recent work and suggestions of Hamilton (9, 10) that the larger mapped plutons of western Nevada and adjacent California *may actually be composed of many smaller intrusives.*

tricts, Cretaceous and younger intrusive aphanitic textured rocks, (porphyritic and wholly aphanitic) of intermediate to acid composition, are present in bodies of extensive size and quantity occurring either alone or accompanied by granitoid rocks.

DEFINITION OF TEXTURES

Because texture is the basis for the distinctions made in this report, clarification of the textural terms as used herein must be made. The term "granitoid" is applied in its well-established historical sense to indicate a non-foliated or non-stratified rock in which all minerals are visible to the unaided eye. Pegmatites are excluded from this category, but it includes granitoid rocks containing large phenocrysts as, for example, porphyritic granite. Rocks described as possessing on "aphanitic" texture appear to be crystalline, but mineral grains are too small to be perceived with the unaided eye. The terms "porphyry" or "porphyritic texture" have reference to rocks possessing an aphanitic groundmass and visible phenocrysts. It will be immediately recognized that confusion often results in the use of these terms when "porphyritic" may be applied to a "granitoid" as well as to an "aphanitic" rock.

In perusing the literature on the Basin and Range Province, it is interesting to note that many writers have been quite thorough in their recognition, distinction, and reporting of the various textures of intrusive rocks. Others, however, have tended to lump intrusive aphanite porphyries together with granitoid rocks in their mapping and classification scheme, thus causing a reader great difficulty in ferreting out of the literature the true nature and distribution of these two types. In view of the importance of a clear-cut distinction of rock types to the exploration geologists and future researchers, it is hoped that such inconclusive reporting will be avoided in the future.

STATISTICS OF INTRUSIVES OF THE MINING DISTRICT

Method of Presentation.—Systematic presentation and acknowledgment of the specific information acquired on each of the 107 districts studied, new or reviewed from the works of others, would be too extensive and not necessary for this paper. The problem of presentation and acknowledgment is partly solved by listing the districts in Table I, giving the best publication or publications dealing with the geology of the district, and by adding statements of personal observations and personal communication, only where necessary to clarify the geology. An explanation of the writer's classification is interjected where it many conflict with the information contained in the cited reference. The reader may thus check for himself the geology of each district upon which the statistics and conclusions of this work are based.

Evaluation of the geological conditions of intrusives in each of the mining districts considered is made in the accompanying tabulations. The districts are segregated into production categories based on value of total production and arbitrarily selected as $3,000,000 to $5,000,000, $5,000,000 to $10,000,000, $10,000,000 to $25,000,000, $25,000,000 to $50,000,000 and over $50,000,000. Production figures here are not current and are intended

TABLE 1

107 Districts Investigated of the Basin and Range Province, U.S.A., Regarded as Hydrothermal Deposits and Which Have Produced over $3,000,000 in Gold, Silver, Copper, Lead, Zinc, Mercury, Tungsten, Molybdenum, and Uranium, Are Listed with Accompanying Geological References and Annotations

Districts with an asterisk (*) have been observed firsthand by the author

Agua Fria, Arizona
Jaggar, 1905, U.S.G.S. Geol. Folio 126
Lindgren, 1926, U.S.G.S. B.782, 146–149
Ajo, Arizona
Gilluly, 1946, U.S.G.S. P.P. 209
Gilluly, 1938, Ariz. Bur. Min. B.145, 86–90
Aravaipa, Arizona
Ross, 1925, U.S.G.S. B.763
Aurora, Nevada
Hill, 1915, U.S.G.S. B.594, 141–150
Hill's account of Aurora is based upon very brief field observation and his intrusive andesite porphyry (page 145), though definitely located in the field could not certainly be confirmed as to its intrusive nature. More work is needed here to establish clearly the true geological conditions.
Austin (Reese River), Nevada
Hill, 1915, U.S.G.S. B.594, 95–114
Ross, 1953, U.S.G.S. B.997
Bagdad, Arizona
Anderson, 1955, U.S.G.S. P.P. 278
Belmont, Nevada
Hughes, 1917, E. & M. J. 1007–1008
Hughes' account is very brief. The district should be more completely studied and reported.
Berlin, Nevada
Ferguson, 1949, U.S.G.S. P.P. 216
Charles J. Vitaliano, U. of Indiana, reports that no intrusive of any sort is exposed in or near the Berlin Mine.
Big Bug, Arizona
Creasey, 1950, Ariz. Bur. Min. B.156, 112–122
Creasey, 1952, E. G. 47, 24–56
Lindgren, 1926, U.S.G.S. B782, 126–145
Bingham, Utah
Boutwell, 1905, U.S.G.S. P.P. 38
Butler, 1920, U.S.G.S. P.P. 111, 335–362
Stringham, 1953, G. S. A. B.64, 945–991
Bisbee, Arizona
Hogue, 1950, Ariz. Bur. Min. B.156, 17–29
Ransome, 1904, U.S.G.S. P.P. 21
Ransome, 1904, U.S.G.S. Geol. Folio 112
Blind Spring Hill, California
Ransome, 1940, Cal. State Miner. Rep. 36, 159–197
Bodie, California
Eakle, 1915-16, Cal. State Miner. Rep. 15, 149–160
Charles W. Chesterman, San Francisco, Cal. "Andesite dikes clearly later than the main body of andesite have been found in many of the larger mines. These dikes came in along faults and have been subjected to post-implacement alteration."
Bristol, Nevada
Hill, 1916, U.S.G.S. B.648, 124–137
Knopf, 1932, U.S.G.S. P.P. 171, 68–70
Lawrence K. Requa, Salt Lake City, "No intrusives crop out on the surface but several dikes have been exposed underground."
Bullfrog, Nevada
Ransome, 1910, U.S.G.S. B.407
Bullion, Nevada
Emmons, 1910, U.S.G.S. B.408, 89–95
Calico, California
Erwin, 1940, Cal. J. Mines and Geol. 36, 293–304 (esp. page 296)
Candelaria, Nevada
Knopf, 1823, U.S.G.S. B.735a, 1–22
Castle Dome, Arizona
Peterson, 1951, U.S.G.S. B.971
Central (Santa Rita), New Mexico
Lasky, 1936, U.S.G.S. B.870
Spencer, 1935, U.S.G.S. B.859
Cerro Gordo, California
Knopf, 1914, U.S.G.S. B.540b, 81–120
Knopf, 1918, U.S.G.S. P.P. 110, 108–116
Cherry Creek, Nevada
Hill, 1916, U.S.G.S. B.648, 161–171
Detailed mapping of the area reveals only granitoid intrusives other than small porphyry dikes.
Chloride (Mineral Park, Cerbat), Arizona
Dings, 1951, U.S.G.S. B.978 e, 123–163
Schrader, 1909, U.S.G.S. B.397, 51–80
Thomas, 1949, E. G., 44, 663–705
Chloride Flat, New Mexico
Graton, 1910, U.S.G.S. P.P. 68, 601–605
Paige, 1916, U.S.G.S. Geol. Folio 199
Christmas, Arizona
Peterson, 1956, U.S.G.S. B.1027 h
Ross, 1925, U.S.G.S. B.771, 20, 52–60
Congress, Arizona
Wilson, 1934, Ariz. Bur. Min. B.137, 69–73
Copper Basin (Battle Mtn.), Nevada
Hill, 1915, U.S.G.S. B.594, 64–91
Roberts, 1951, U.S.G.S. Geol. Quad. Map No. 10
Copper Canyon (Battle Mtn.), Nevada
Hill, 1915, U.S.G.S. B.594, 64–91
Roberts, 1951, U.S.G.S. Geol. Quad. Map No. 10
The intrusive plug at Copper Canyon, though designated on Robert's map as quartz monzonite, was found in the field to be largely quartz monzonite porphyry.
Cortez, Nevada

TABLE 1—*Continued*

Emmons, 1910, U.S.G.S. B.408, 100–106
**Cottonwood-American Fork, Utah*
Calkins, 1920, U.S.G.S. P.P. 111, 227–254
Calkins, 1943, U.S.G.S. P.P. 201
**Courtland Gleeson, Arizona*
Gilluly, 1956, U.S.G.S. P.P. 281, 90–92, plate 11
Wilson, 1927, Ariz. Bur. Min. B.123
**Darwin, California*
Kelley, 1938, Cal. J. Min. and Geol. 34, 504–563
Knopf, 1915, U.S.G.S. B.580 a, 1–18
Knopf's report that areas of granite porphyry and quartz diorite porphyry occur in the Darwin quartz diorite (Knopf, 1915, p. 6) was confirmed in the field.
**Delamar, Nevada*
Callaghan, 1937, Nev. U. B.31, no. 5
Divide, Nevada
Knopf, 1920, U.S.G.S. B.715 k, 147–170
**Eldorado, Nevada*
Ransome, 1907, U.S.G.S. B.303, 63–79
This very brief geological account is not entirely satisfactory. The included geological sketch map could not be confirmed in the field except in a general way.
**Ely, Nevada*
Spencer, 1917, U.S.G.S. P.P. 96
**Eureka, Nevada*
Hague, 1892, U.S.G.S. Monograph, 20
Nolan, 1956, U.S.G.S. P.P. 276
Nolan, T. B., Prelim. Geol. Map, Unpublished
**Fairview, Nevada*
Greenan, 1914, E. & M. J., 97, 791–793
**Getchell, Nevada*
Hobbs, 1946, Nev. U. B.40, no. 5
Joralemon, 1951, E. G. 46, 267–310
**Gold Acres, Nevada*
Gates, 1956, Tertiary volcanism and brecciation, Shoshone Range, Nev. Johns Hopkins U. Thesis, Plate 1B
Keith B. Ketner, U.S.G.S. "On the west face of the present mine workings (Gold Acres) where a north–south section is exposed, the intrusive appears to be a lens as much as 100 feet thick and several hundred feet long. Its east–west extent is unknown. Although it generally parallels the bedding in overlying rocks, it cuts across locally." Thin section study of one unaltered specimen from this intrusive serves to classify it tentatively as an andesite porphyry.
**Goldfield, Nevada*
Ransome, 1909, U.S.G.S. P.P. 66
**Gold Hill, Utah*
Nolan, 1935, U.S.G.S. P.P. 177
Nolan states (p. 45) that the quartz monzonite at Gold Hill shows ". . . apparently a gradation between porphyritic quartz monzonite and a rock that is more properly termed quartz monzonite porphyry." The magnitude of the porphyry portion is not given and was not checked in the field, hence Gold Hill is placed in a category as a district without significant intrusive porphyry. Future work may serve to alter this classification.
**Goodsprings, Nevada*
Hewitt, 1931, U.S.G.S. P.P. 162
**Hamilton, Nevada*
Larsh, 1909, Mines & Minerals, 29, 521–523
**Harquahala, Arizona*
Bancroft, 1911, U.S.G.S. B.451, 105–108
**Harshaw, Arizona*
Schrader, 1915, U.S.G.S. B.582, 245–279
Schrader's reported granodiorite porphyry was confirmed in the district.
**Helvitia, Arizona*
Creasey, 1955, U.S.G.S. B.1027 f
Schrader, 1915, U.S.G.S. B.582, 91–138
**Hillsboro, New Mexico*
Harley, 1934, N. Mex. Sch. Min. B.10, 125–169
Kuellmer, 1955, N. Mex. Inst. Min. and Tech., Cir. 34
**Jarbidge, Nevada*
Schrader, 1923, U.S.G.S. B.741
Robert R. Coats, U.S. Geol. Sur.
"The intrusive dikes described by Schrader seem to be less than 100 feet across, - - -. I have not found any plug-like intrusive porphyry masses in the Jarbidge area. There are some shallow intrusive or extrusive domes of rhyolitic composition on the north side of Jack Creek valley, about a mile above the mouth." The point referred to in Jack Creek valley, is 3 miles north of Jarbidge.
**Jerome, Arizona*
Huff, 1955, U.S.G.S. B.1000 c, 105–118
Lindgren, 1926, U.S.G.S. B.782, 54–93
Johnson, Arizona
Baker, 1953, Min. Eng. 5, 1272–1277
Cooper, 1950, Ariz. Bur. Min. B.156, 30–39
**Kingston, New Mexico*
Harley, 1934, N. Mex. Sch. Min. B.10, 98–125
Kuellmer, 1954, N. Mex. Inst. Mines, B.33
**Kofa, Arizona*
Jones, 1915, U.S.G.S. B.620 h, 151–164
A superficial measurement of some of the porphyry dikes at Kofa suggests that one or two may be considerably over 100 feet thick.
**Lewis, Nevada*
Emmons, 1910, U.S.G.S. B.408, 122–126
Gates, 1954, Tert. Vol. & Breccia., Shoshone Range, Nev., Johns Hopkins U. Ph.D. Thesis
**Lordsburg, New Mexico*
Lasky, 1938, U.S.G.S. B.885
**Lucin, Utah*
Butler, 1920, U.S.G.S. P.P. 111, 488–494

TABLE 1—*Continued*

Detailed mapping in the North Pilot Range, Utah reveals that there is no significant intrusive porphyry exposed in the vicinity of the Lucin ore bodies.
**Ludlow, California*
Gardner, 1940, Cal. J. Min. and Geol. 36, 257–292
**Magdalena, New Mexico*
Loughlin, 1942, U.S.G.S. P.P.200
**Mammoth, Arizona*
Peterson, 1938, Ariz. Bur. Min. B.144
**Manhattan, Nevada*
Ferguson, 1924, U.S.G.S. B.723
Ferguson, 1954, U.S.G.S. Geol. Quad. No. 40
**Marysvale, Utah*
Kerr, 1957, G.S.A. Spec. Pap. 64
**Mercur, Utah*
Gilluly, 1932, U.S.G.S. P.P.173
**Miami, (Globe, Copper Cities, Inspiration), Arizona*
Peterson, 1950, Ariz. Bur. Min. B.156, 98–112
Peterson, 1954, E. G. 49, 362–377
Peterson, 1954, U.S.G.S. Quad. Map No. 41
Ransome, 1905, U.S.G.S. Folio 111
Ransome, 1919, U.S.G.S. P.P. 115
Mill City, Nevada
Kerr, 1934, Nev. U. B.28, No.2
**Mogollon, New Mexico*
Ferguson, 1927, U.S.G.S. B.787
Mohave, California
Bateson, 1906, AIME Tr. 37, 160–177
DeKalb, 1907, AIME Tr. 38, 310–319
Schroter, 1935, E. & M. J. 136, 185–188
Willard C. Gere, U.S.G.S., Salt Lake City, "Intrusive porphyry consisting predominantly of rhyolites exists in the immediate Mohave Mining district."
**Morenci, Arizona*
Butler, 1938, Ariz. Bur. Min. B.145, 72–80
Lindgren, 1905, U.S.G.S. P.P. 43
**Mountain City, Nevada*
Emmons, 1910, U.S.G.S. B.408, 80–83
**National, Nevada*
Lindgren, 1915, U.S.G.S. B.601
**Oatman, Arizona*
Lausen, 1931, Ariz. Bur. Min. B.131
Ransome, 1923, U.S.G.S. B.743
**Ophir, Utah*
Gilluly, 1932, U.S.G.S. P.P. 173
**Park City, Utah*
Boutwell, 1912, U.S.G.S. P.P. 77
Butler, 1920, U.S.G.S. P.P. 111, 285–317
**Patagonia, Arizona*
Schrader, 1915, U.S.G.S. B.582, 292–348
**Pearce, Arizona*
Gilluly, 1956, U.S.G.S. P.P. 281, 116–118
Smith, A., 1927, Geol. Commonwealth Mine, Thesis, U. Ariz.
One of the dikes reported by Smith to be in the Pearce area was confirmed in the field.
**Peck-Crown King, Arizona*
Jaggar, 1905, U.S.G.S. Geol. Folio 126
Lindgren, 1926, U.S.G.S. B.782, 160–164
Stanley E. Jerome, Salt Lake City, Utah. Though there is no stratigraphic proof, Jerome agrees with Lindgren and regards the plutonic intrusions in the vicinity of Crown King as probably forming very late.
**Pinos Altos, New Mexico*
Paige, 1910, U.S.G.S. B.470 b, 109–125
Paige, 1916, U.S.G.S. Geol. Folio 199
**Pioche, Nevada*
Westgate, 1932, U.S.G.S. P.P. 171
**Planet-Swansea, Arizona*
Bancroft, 1911, U.S.G.S. B.451, 47–55
**Randsburg, California*
Hulin, 1925, Cal State Min. Bur. B.95
**Ray, Arizona*
Clarke, 1952, Ariz. Geol. Soc. Guidebook, April, 91–95
Ransome, 1919, U.S.G.S. P.P. 115
**Rochester, Nevada*
Knopf, 1924, U.S.G.S. B. 762
**Round Mountain, Nevada*
Ferguson, 1921, U.S.G.S. B.725 i, 383–406
Ferguson, 1954, U.S.G.S. Geol. Quad. Map No. 40
**San Francisco, Utah*
Butler, 1913, U.S.G.S. P.P. 80
Butler states (page 53) "Towards the margins of the stock the quartz monzonite is usually fine grained and porphyritic. This fine texture, however, does not appear to be confined entirely to contact types, as the ridge west of Indian Grove Peak (1¼ miles northwest of the Horn Silver Mine) is composed of a fine uniform-textured rock. . . . The porphyritic type is well shown in the point extending to the east, where all the rock is fine grained and much of it is distinctly porphyritic." The porphyry of the "eastern lobe" located directly west of the old Carbonate mine was confirmed in the field. The San Francisco district is thus placed in the "porphyry" category with the realization that more work is needed to thoroughly establish this relationship.
**San Manuel, Arizona*
Pelletier, 1957, Min. Eng. 9, No. 7 July, 760–763
Schwartz, 1953, U.S.G.S. P.P. 256
**Searchlight, Nevada*
Callaghan, 1939, U.S.G.S. B.906-D, 135–188
Ransome, 1907, U.S.G.S. B.303, 63–75
**Seven Troughs, Nevada*
Ransome, 1909, U.S.G.S. B.414, 14–25
Shafter, Texas
Ross, 1943, U.S.G.S. B.928-B
**Silver Bell, Arizona*
Kerr, 1951, G.S.A. B.62, 451–480
Richard & Courtright, 1954, Mg. Eng. 6, 1095–1099

TABLE 1—*Continued*

Silver Peak, Nevada
Spurr, 1906, U.S.G.S. P.P. 55
Turner, 1909, G.S.A. B.20, 223–264
Spurr's designation of the Silver Peak ores as Postcambrian was questioned by Turner who did the major portion of the Silver Peak field mapping. Following a brief examination of this area the writer agrees with Turner that the deposits appear to be Precambrian in age.
Steeple Rock, New Mexico
Lindgren, 1910, U.S.G.S. P.P. 68, 327–328
Russell, 1947, U.S. Bur. Min. R. I. 4073
Stockton, Utah
Gilluly, 1932, U.S.G.S. P.P. 173
Superior, Arizona
Ransome, 1914, U.S.G.S. B.540 d, 139–158
Short, 1943, Ariz. Bur. Min. B.151
Tenabo, Nevada
Emmons, 1910, U.S.G.S. B.408, 114–118
Gates, 1956, Tert. Vol. & Breccia., Shoshone Range, Nev., Johns Hopkins Univ. Thesis, Plate 1 B
Gates' map shows intrusive porphyry associated with the granitoid pluton at Tenabo
Terlingua, Texas
Ross, 1941, E. G. 36, 115–142
Tintic, Utah
Lindgren, 1919, U.S.G.S. P.P. 107
Lovering, 1949, E. G., Mon. 1
Tombstone, Arizona
Butler, 1938, Ariz. Bur. Min. B.143
Butler, 1938, Ariz. Bur. Min. B.145, 104–110
Gilluly, 1945, Am. J. Sc. 243, 643–666
Gilluly, 1956, U.S.G.S. P.P. 281
Tonopah, Nevada
Nolan, 1930, Nev. U. B.24, No. 4
Nolan, 1935, Nev. U. B.29, No. 5
Spurr, 1905, U.S.G.S. P.P. 42
Tuscarora, Nevada
Emmons, 1910, U.S.G.S. B.408, 57–61
Nolan, 1936, Nev. U. B.30, No. 1
Twin Buttes, (Pima, Sierrita) Arizona
Mayuga, 1942, U. Ariz. Ph.D. Thesis
Ransome, 1922, U.S.G.S. B.725, 407–440
Thurmond, 1954, Min. Eng. 6, 197–202
J. H. Courtright, Tucson, Ariz. ". . . it can be definitely stated that at least two intrusive porphyries occur in the vicinity of Mineral Hill and Helmet Peak, or the northern part of the Twin Buttes district. One of these, a biotite rhyolite with an aphanitic groundmass, occurs as stock-like masses several thousand feet in diameter. The other is a monzonite porphyry having what appears to have been originally (prior to alteration) a rather fine granular groundmass. It occurs in the form of stocks, dikes and sills."
Tybo, Nevada
Ferguson, 1933, Nev. U. B.27, No. 3
Tyrone, New Mexico
Paige, 1911, U.S.G.S. B.470 c, 131–150
Paige, 1922, U.S.G.S. P.P. 122
Unionville, Nevada
Cameron, 1939, G.S.A. B.50, 563–633
Virginia City, Nevada
Thompson, 1956, U.S.G.S. B.1042 e, 45–77
Vulture (Wickenburg), Arizona
Wilson, 1934, Ariz. Bur. Min. B.137, 157–161
White Hills, Arizona
Schrader, 1909, U.S.G.S. B.397, 127–134
Wonder, Nevada
Ritter, 1909, E. & M. J. 87, 289–292
Though Ritter's account is brief, the intrusive porphyry was readily confirmed in the field.
Yerington, Nevada
Knopf, 1918, U.S.G.S. P.P. 114

only to indicate an order of magnitude. Future production may add new districts to the lists and move some districts to a higher category. Some may have already achieved these distinctions. The writer hopes that no mining district of the sort considered, within the Basin and Range Province, deserving of being listed here has been omitted. If such is the case it is an oversight.

Classification of Districts as to Type of Intrusives.—Table 2 shows that in 39 of the 107 mining districts porphyry or aphanite is the only intrusive rock present. It should be explained that in a district where granitoid rocks of Precambrian age occur with an intrusive porphyry of Cretaceous or later age, the district is nevertheless placed in this category as, for example, Morenci, San Manuel, and Bisbee. At Pioche, the only intermediate to acid intrusive present within miles of the mineralized district is a dike known as the Yuba dike. At Bristol, no known intrusive is present at the surface but several porphyry dikes have been encountered underground. At Kofa, Pearce, Jarbidge, and Bodie the only known intrusives are porphyry dikes. The remain-

der of the districts shown on Table 2 all contain large dikes, sills (a large dike or sill is considered here to be over 100 feet thick) pipes, breccias having an igneous matrix with aphanitic texture or most commonly cross cutting stock-like bodies all composed of aphanitic textured rocks, (includes porphyry).

Table 3 lists 46 of the 107 districts categorized as to production in the same manner as Table 2. These districts contain stocks of granitoid rocks associated with various types of intrusive porphyries. No districts wherein small dikes are the only aphanitic intrusives present are included here, rather, each district contains a large extensive area of porphyry intrusive, such as sills and dikes larger than 100 feet in thickness and stocks and plugs, generally

TABLE 2

MINING DISTRICTS CONTAINING INSTRUSIONS OF APHANITE OR PORPHYRITIC APHANITE ONLY, UNACCOMPANIED BY GRANITOID ROCKS

Over $50,000,000	$25–50,000,000	$10–25,000,000	$5–10,000,000	$3–5,000,000
Arizona	Arizona	Arizona	Arizona	Arizona
Bisbee	Oatman	Christmas	*Kofa	Mammoth
Morenci		*Pearce		
San Manuel	California		California	Nevada
	*Bodie	California	Ludlow	Bullfrog
Nevada	Cerro Gordo	Calico		Divide
*Pioche			Nevada	National
Tonopah	Nevada	Nevada	*Bristol	Seven Troughs
	Aurora	Candelaria	Fairview	
		Copper Canyon	Gold Acres	
	Utah	Goodsprings	Rochester	
	Ophir	*Jarbidge	Unionville	
	Stockton	Tuscarora	Wonder	
		Tybo	New Mexico	
		New Mexico	Kingston	
		Mogollon	Steeple Rock	
		Texas		
		Shafter		
		Terlingua		
		Utah		
		Mercur		

* Aphanites present as dikes only.
Total = 39 Districts.

of much greater dimension. It is noted that one district, Jerome, is a Precambrian age whereas the others are considered to be Cretaceous or younger.

Table 4 lists the remaining 22 of the 107 districts categorized as before. In 18 districts shown on Table 4 granitoid rocks occur alone without a significant amount of intrusive aphanite other than small dikes and sills. In 4 districts, intrusives of any sort are unknown. Note that there is not a single district here in the category over $50,000,000 and that Austin and Cottonwood-American Fork, are the only districts in the $25–50,000,000 column and also that Planet-Swansea, the largest producer not associated with an intrusive, has yielded less than $10,000,000 production. There are 3 other important features to note concerning these occurrences. The 10 districts that are

TABLE 3

MINING DISTRICTS CONTAINING INTRUSIONS OF APHANITE OR PORPHYRITIC APHANITE AND GRANITOID ROCKS

Over $50,000,000	$25–50,000,000	$10–25,000,000	$5–10,000,000	$3–5,000,000
Arizona	Arizona	Arizona	Arizona	Arizona
Ajo	Bagdad	Castle Dome	Patagonia	Aravaipa
*Jerome	Silver Bell	Chloride		Harshaw
Miami-Globe	Tombstone	Courtland-Gleeson	Nevada	Helvitia
(Inspiration)	Twin Buttes		Copper Basin	
(Copper Cities)		Nevada	Searchlight	California
Ray	California	Delamar		Mohave
Superior	Darwin	Hamilton	New Mexico	
	Randsburg	Manhattan	Hillsboro	Nevada
Nevada		Round Mtn		Bullion
Eureka	New Mexico			Eldorado
Goldfield	Lordsburg	New Mexico		Lewis
Virginia City	Magdalena	Pinos Altos		Tenabo
Yerington		Tyrone		
	Utah			New Mexico
New Mexico	San Francisco	Utah		Chloride Flat
Central		Marysvale		
(Santa Rita)				
(Bayard)				
Utah				
Bingham				
Park City				
Tintic				

* Deposit Precambrian.
Total = 46 Districts.

starred (Table 4) namely Austin, Mountain City, Cortez, Getchell, Blind Spring Hill, Johnson, Cherry Creek, Gold Hill, Berlin, and Lucin, have ore bodies or plutons situated close to either over-lapping younger sediments or lavas. These districts, therefore, could possibly have an obscured intrusive porphyry present within the area of the district. Considering the abundance of younger lavas and sediments within the Basin and Range Province it is surprising that more of the districts do not fall into this situation. In 4 districts only, Cottonwood-American Fork, Belmont, Peck-Crown King, and Mill City, the intrusives are granitoid and outcrops are so extensive and the regions so well studied it can confidently be concluded that no large intrusions of porphyry are known to be associated within reasonable distances of the ore deposits. The 8 areas with double star (Table 4), that is Silver Peak, Big Bug, Planet, Congress, White Hills, Haraquahala, Vulture, and Agua Fria are considered to be Precambrian in age. It is interesting to note that at Mill City and Getchell, the largest production has been in tungsten. In the cases of other smaller tungsten producing districts, for instance at Round Mountain and Atolia, near Randsburg, the ore occurs mainly associated with granitoid intrusives rather than aphanitic ones. The formation of hydrothermal or contact tungsten deposits, therefore, seems to be more closely related to the development of granitoid bodies than to aphanitic bodies.

Figure 1 is a diagram showing the percentages of all these districts in their several associations. In round numbers, 36 percent or 39 of the 107 districts have porphyritic aphanite intrusives alone, 43 percent or 46 districts show granitoid as well as porphyritic intrusives, 17 percent or 18 districts have granitoid intrusives only, and 4 percent or 4 districts show no associated intrusives of any kind.

Including only Jurassic and later deposits in a similar comparison thus excluding 9 districts (including Jerome) considered to be of Precambrian age (Fig. 2) the percentages would be as follows: Of 98 districts qualifying

TABLE 4

MINING DISTRICTS CONTAINING INTRUSIONS OF GRANITOID ROCK ONLY, OTHER THAN SMALL DIKES OR SILLS

Over $50,000,000	$25–50,000,000	$10–25,000,000	$5–10,000,000	$3–5,000,000
	Nevada *Austin Utah Cottonwood- American Fork	Arizona ‡Big Bug Nevada Mill City *Mountain City ‡Silver Peak	Arizona ‡Congress *Johnson Peck-Crown King ‡Vulture California *Blind Spg. Hill Nevada Belmont *Cortez *Getchell Utah *Gold Hill	Arizona ‡Agua Fria Nevada *Cherry Creek Utah *Lucin
MINING DISTRICTS WITH NO KNOWN APHANITIC OR GRANITOID INTRUSIVES				
			Arizona ‡Planet-Swansea	Arizona ‡Harquahala ‡White Hills Nevada *Berlin

* Aphanite intrusives could occur under immediately adjacent cover of lava or sediments.
‡ Deposits considered Precambrian.
Total = 22 Districts.

for this category, 85 districts or 86 percent in all would have intrusive aphanite with or without granitoid rocks. Of these, 39 districts or 40 percent would contain aphanite only and 45 districts or 46 percent would have both aphanite and granitoid intrusives. Ten districts, 9 containing granitoid rocks only, and one without any known intrusive, or 10 percent in all could have intrusive aphanites present, but due to adjacent cover such aphanites may be obscured. In 4 percent (Cottonwood-American Fork, Mill City, Belmont, and Peck-Crown King) it seems certain that no porphyritic aphanite could accompany the associated granite and one of these (Mill City) produces tungsten only.

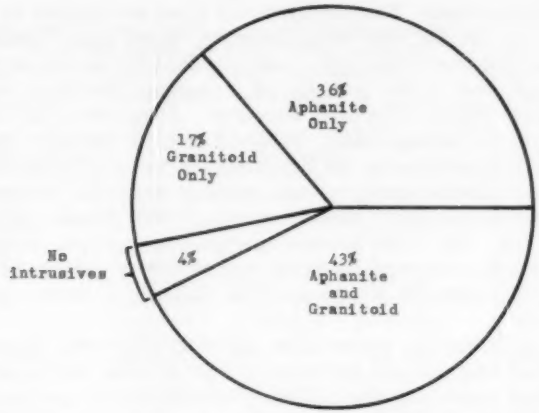

FIG. 1. Diagram summarizing the intrusive rock textures of 107 mining districts.

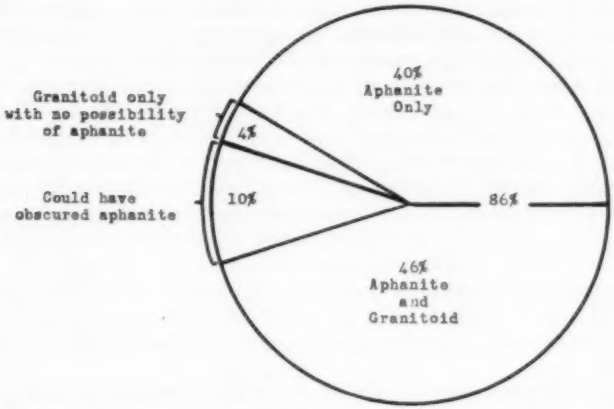

FIG. 2. Diagram summarizing the intrusive rock textures of 98 Cretaceous and younger deposits, excluding 9 districts of Precambrian age.

GENERALIZATIONS OF THE STATISTICS

A compositional comparison of the associated or parent intrusive porphyritic types exposed in the various districts with the kind of metal produced is of interest because it indicates but very little correlation of the intrusive type to kind of metal present, excepting that definitely related larger basic intrusives (basalts, diabase, gabbros and more basic) are absent. In many deposits small late basic dikes are ubiquitous, however. Table 5 is a tabulation of the intrusive porphyry present in each of the 85 districts listed accord-

ing to composition. The porphyry rock types as classified by each individual worker are divided into three categories based upon "acidity." In a few districts, 2 or more rock types were classified by the major investigator and some confusion in the selection of a category for these districts resulted (examples, Virginia City and Morenci). Thus, there may be disagreement in some of the listings made. Where 2 or more intrusive types are present, however, that rock having the larger outcrop was used in the listings. Diorite porphyry, andesite porphyry, and andesite constitute the more basic group while granite porphyry, rhyolite porphyry and rhyolite make up the most "acidic" list. All of the intermediate types are grouped as granodiorite porphyry, quartz monzonite porphyry, quartz latite porphyry and latite porphyries together with the wholly aphanitic varieties of dacite, quartz latite, and latite.

Of the 20 districts shown under diorite porphyry etc., 2 produce copper as the major metal, 14 gold and silver, 3 lead and zinc, and 1 mercury, Of the 32 districts containing granodiorite porphyry etc. as associated intrusive, 19 produce chiefly copper, 7 gold and silver and 6 lead and zinc. The 33 most "acid" districts show 7 producing mainly copper, 19 gold and silver, 6 lead and zinc, and 1 uranium. The more or less equal distribution of the intrusive rock types as compared with the major metal production suggests very little correlation of metal with rock type, excepting in the case of copper, where there is a somewhat larger number in the "intermediate" column. It is here that most of the disseminated deposits belong. It should be noted, however, that 5 very large copper districts, Bingham, Morenci, Miami, Bisbee, and Jerome are in the "acid" category. An observation as to the general relationship and expectabilities of kind of hydrothermal ore deposits to type of intrusive porphyry within the Basin and Range, indicates that except for minor small dikes, ore deposits are not genetically associated with intrusive aphanites more basic than andesite or diorite porphyry. Further, there is no special correlation between kinds of ore and intrusive rocks except in the case of copper deposits that show some preferential association with the "intermediate" rocks. In mineral exploration larger basic intrusives could be safely ignored and potential discovery increased in areas of intermediate to acid type intrusive porphyries.

A generalization based entirely on observable exposures involving the size of the intrusive aphanite compared with the magnitude of the associated ore deposit is justified. If the exposure of the associated aphanite is large (approximately over 1,000 feet in smallest dimension) the chances of encountering a large ore body are better than if the intrusive is small. There are several exceptions to this rule, however, such as Superior and Pioche, both large districts where the intrusives are small. Conversely at Tombstone and Aravaipa, very large outcrops of porphyry are exposed with comparatively small associated known ore deposits. This criteria, based mainly on 2 dimensional data, could be valid for more cases if the volume, attitude and 3 dimensional shape of the intrusive is considered along with the various depths to which erosion may have exposed it.

TABLE 5

85 DISTRICTS WITH PORPHYRY INTRUSIVES ONLY, CLASSIFIED ACCORDING TO ROCK COMPOSITION AND MAJOR METAL PRODUCED

Diorite Porphyry–Andesite		Quartz Monzonite Porphyry–Latite		Granite Porphyry–Rhyolite	
	Major Metal		Major Metal		Major Metal
1 Pearce	AuAg	San Manuel	Cu	Morenci	Cu
2 Superior	Cu	Christmas	Cu	Bisbee	Cu
3 Mogollon	AuAg	Ray	Cu	Oatman	Au
4 Steeple Rock	PbZn	Ajo	Cu	Kofa	Au
5 Pinos Altos	Cu	Tombstone	AuAg	Mammoth	AuAg
6 Tonopah	Ag	Castle Dome	Cu	Jerome	Cu
7 Aurora	Au	Silver Bell	Cu	Miami-Globe	Cu
8 Tuscarora	AuAg	Courtland-Gleeson	Cu (AgAu)	Chloride	AuAg
9 Fairview	AuAg	Patagonia	Cu	Aravaipa	PbZn
10 Divide	AuAg	Helvitia	Cu	Lordsburg	Cu
11 Virginia City	AuAg	Harshaw	Pb (Ag)	Pioche	PbZn
12 Searchlight	AuAg	Bagdad	Cu	Goodsprings	PbZn
13 Eldorado	AuAg	Twin Buttes	Cu	Jarbidge	Au
14 Tenabo	AuAg	Kingston	PbZn (Cu)	Bristol	Pb (Ag)
15 Lewis	AuAg	Central	Cu (PbZn)	Wonder	AuAg
16 Gold Acres	Au	Magdelena	Pb (Zn)	Rochester	Ag
17 Bodie	Au	Tyrone	Cu	Unionville	Ag
18 Park City	PbZn (Ag)	Hillsboro	Cu (AgAu)	National	Au
19 Shafter	PbZn	Chloride Flat	Cu	Seven Troughs	AuAg
20 Terlinqua	Hg	Tybo	Ag	Bullfrog	AuAg
21		Copper Canyon	Cu	Delamar	Au
22		Candelaria	AuAg	Hamilton	Ag
23		Ely	Cu	Manhattan	Au
24		Yerington	Cu	Round Mtn	Au
25		Goldfield	Au	Bullion	Cu (Pb)
26		Eureka	PbZn (Ag)	Calico	Ag
27		Copper Basin	Cu	Ludlow	Ag
28		Cerro Gordo	Ag (Pb)	Mohave	AuAg
29		Randsburg	Ag	Ophir	PbZn
30		Darwin	PbZn (Ag) (W)	Mercur	Au
31		Stockton	PbZn	Bingham	Cu (PbZn)
32		San Francisco	Ag (PbZn)	Marysvale	U PbZn
33				Tintic	PbZn (Ag)
2 districts	Cu	19 districts	Cu	7 districts	Cu
14 districts	AuAg	7 districts	AuAg	19 districts	AuAg
3 districts	PbZn	6 districts	PbZn	6 districts	PbZn
1 districts	Hg			1 districts	U

The intrusive aphanite is generally present within a radius of 2 miles of its associated mineral deposit. The chief exceptions of the rule are at Hamilton and Rochester.

BARREN INTRUSIVE APHANITES

Extensive intrusive aphanites do exist in some areas without significant quantities of exposed associated economic mineralization. For instance, in two of the barren intrusive areas studied in the Eastern Great Basin men-

tioned earlier, most of the outcrop is of aphanitic texture. Many examples of intrusive porphyritic rock not associated with mineralization have been noted in the literature. Sufficient information on which to base a valid statistical analysis is not available on these areas and will not be available until many more plutons in the Basin and Range Province are carefully mapped and studied. Consequently no statement or speculation can be advanced at the present time as to the similarities or differences between a productive and a barren intrusive porphyry. The next logical step in a study of this nature is to try to determine if there is a real, recognizable difference existing between the two. Obviously, if this can be done successfully, further evaluation can be offered to the ore finder upon his discovering a large intrusive porphyry in the field.

GEOLOGICAL PROCESSES INVOLVED

It is not within the scope of this paper to speculate upon the explanations of the porphyry–ore association of the Basin and Range Province that have become apparent through these studies. In a general way it can safely be concluded, however, that the geological processes which make or form an intrusive aphanitic textured rock of intermediate to acid composition, whatever those processes may be, are also capable of forming associated economic hydrothermal ore deposits, and further that the geologic processes which form a granitoid rock, of intermediate to acid composition, whatever those processes may be, are *not* capable of forming large hydrothermal ore deposits. Theoretical considerations relating to these findings will be discussed in the near future.

PREVIOUS REFERENCES TO THE PORPHYRY–ORE ASSOCIATION

In 1919 Ransome (17, page 166) recognized that quartz monzonite porphyry or related intermediate porphyry was always an associated intrusive rock in the disseminated copper deposits of the southwest but suggests that the now visible parts of the porphyry did not contribute actively to ore deposition and that their presence simply is testimony of a larger igneous mass existing below that furnished the energy and at least part of the ore solutions. No further mention of porphyry association to other types of hydrothermal ore bodies was made by him.

Sales (19) suggested that intrusion of porphyry may be an *intermediate* stage of activity between the development of a granitoid intrusive and certain types of copper deposition. This has an excellent basis of fact for the deposits he cites. However, in considering the overall occurrences of copper and other minerals in the Basin and Range Province, 40 percent of the Cretaceous and younger districts contain aphanitic intrusives only and are entirely devoid of granitoid rocks of any sort, thus offering strong statistical evidence that ore producting intrusive porphyry may commonly develop independently of a granite. This percentage is so high it leads one to seriously discount the reasoning that a granite is probably present in these areas at depth and has not been exposed by erosion as yet.

CONCLUSIONS

The practical exploration applications possible as a result of this work seem to be of greatest significance. Statistics of the relationship of intrusive rock textures and mineral production point conclusively to the fact that when exploring in the Basin and Range Province for large Cretaceous or later hydrothermal deposits of gold, silver, lead, zinc, copper, mercury, uranium and molybdenum (tungsten excluded) an intrusive aphanite porphyry of intermediate to acid composition with or without granite, should be present in the district within a distance of 2 miles of the deposit if one expects to find a large mineralized body, at least for 86 percent of the localities. If no porphyritic intrusives are present, one may therefore not expect (for 86 percent of the cases) a large mineralized ore body unless he wished to gamble that adjacent cover obscures the outcrop of such a rock.

In extending this application beyond the borders of the Basin and Range Province, one should at present use great care. However, preliminary observations indicate that the porphyry–ore association may obtain in the Basin and Range region of Mexico, and in other provinces in Western North America especially where the deposits are of more recent age. Certain localities such as Cananea (16), Climax (22), Leadville (3, 6), Cripple Creek (14), Mackay (23), and Butte (19) may be cited as a few of the many examples that show identical intrusive porphyry–ore relationships.

Speculation as to the applicability of these porphyry–ore relationships to Cretaceous and younger mineral deposits throughout the world, is not within the scope of the author's present knowledge and experience. It would seem anomalous, nevertheless, if the relationships described were valid for but one area on the earth's surface such as the Basin and Range Province or even the whole of Western North America. It is the writer's hope that workers geographically removed will test the possibility of a similar association elsewhere.

It is not known yet whether one should pursue intensive exploration in an area of extensive intrusive porphyry where there is little or no mineralization exposed. This problem remains to be investigated.

ACKNOWLEDGMENTS

Appreciation is offered to the administrators of the University Research Fund and the Kennecott Research Fund at the University of Utah who directed financial support to this project. Sincere thanks is also tendered to the many geologists who took time to accompany the writer in the field and to those who freely gave information on various areas. To Armand J. Eardley is extended special regard for his criticism of the manuscript and valuable advice and encouragement throughout the work. Norman C. Williams contributed substantially to the final editing of the paper.

Department of Mineralogy,
University of Utah,
Salt Lake City,
March 20, 1958

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Economic Geology
Vol. 53, 1958, pp. 823–841

GEOCHEMISTRY OF COAL[1]

IRVING A. BREGER

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ABSTRACT

The past decade has witnessed great strides in the accumulation of information about the origin, chemical and physical structure, and composition of coal. These advances were made possible in part by the development of new analytical techniques, and in part by cooperative research between geologists, chemists, physicists, and biologists.

Based on a review of the literature, the consensus is that coal was formed predominantly from lignin. The potential contribution from cellulose or it degradation products is, however, difficult to evaluate. Consideration of sources of energy for the metamorphic processes that convert plant residues into high-rank coals leads to the conclusion that neither bacteria, hydrostatic head, nor localized high temperatures were the geologically active agencies. The application of shear force may provide the energy necessary, but the effectiveness of low-grade thermal activation over long periods of time cannot be overlooked.

The relative importance of aromatic and aliphatic structures, and of the various oxygen-bearing functional groups in coal is now understood in considerable detail. Application of such techniques as adsorption, infrared absorption, and X-ray diffraction has enabled the development of a model for the physical structure of coal through which its colloidal characteristics can be reasonably well explained. The conclusion that coal contains a high concentration of free radicals also helps to explain its color and reactivity.

The concentrations of germanium, uranium, organic sulfur, phosphorus, vanadium, nickel, chromium, beryllium, and rare gases associated with coal have been studied in less detail. For several elements, notably uranium and germanium, attempts have been made to evolve the geochemical principles underlying the mode of concentration of the elements by coals, and the mechanisms by which they are retained.

INTRODUCTION

In 1949 Miller (107) and Cady (28) reviewed the then current problems in coal geochemistry and coal geology and made a number of recommendations for future work. Since that time, a remarkable growth of interest in coal in both academic and industrial circles has led to far-reaching advances in

[1] Publication authorized by the Director, U. S. Geological Survey.

knowledge regarding its origin, chemical constitution, physical structure, and composition. The extent of this interest is perhaps best exemplified by the publication of an unusual number of books on the chemistry of coal within the past ten years by Bangham (4), Kreulen (93), Francis (57), Tomkeieff (147), and van Krevelen and Schuyler (157).

The progress in coal science has undoubtedly stemmed from a new industrial interest in the structure and composition of coal amplified by the development of new analytical techniques and by a growing awareness, fostered and encouraged by Cady (28), of the need for cooperative study between geologist, chemist, and physicist. Although most of the references cited are for studies reported since 1949, a few older key papers are included. The review is limited to progress in the study of humic coals, and no attempt has been made to summarize work on bogheads, cannels, or other similar materials. The literature covered is taken from the fields of geology, chemistry, physics, and biology; under the circumstances the list of references should not be considered complete.

ORIGIN OF COAL

To understand the chemical structure and properties of coal, it is essential that the origin of coal be understood. Although petrographic studies by Thiessen (146) and numerous other workers demonstrated beyond any question of a doubt the origin of coal from plant material, it has been more difficult to determine the chemical constituents that accumulate during the degradation of plant debris. Cellulose, because it is the major constituent of woody plants, was long thought to be the progenitor of coal (8), a view propounded more recently by Berl (10) and by Thiele and Kettner (145). Lignin, on the other hand, was first suggested as the major contributor to the coal substance by Fischer and Schrader (50). Many approaches to a solution of the cellulose-lignin problem have been attempted, particularly during the past 10 years. This activity, catalyzed by the development of new analytical techniques and especially by a rapidly advancing understanding of the chemical structure of lignin (12), has led to a re-evaluation of the Fischer-Schrader theory based on the probable conversion of lignin to humic substances. In this respect, Varossieau (160) and Varossieau and Breger (161) studied ancient buried and decayed wood from both biological and chemical points of view and concluded that hydrolytic processes are active in the decomposition and removal of cellulose, while demethoxylated lignin residues, classifiable as humic substances, are simultaneously formed and accumulate. Additional evidence for the origin of humic substances from lignin, based on infrared studies, was presented by Breger (14). In reviewing the chemical relationships between lignin and humic substances of the soil, Flaig (52) also concluded that lignin must be considered an important progenitor which, upon loss of methoxyl groups, forms phenolic bodies that can polymerize.

Gillet and his co-workers have carried out extensive studies on the pyrolysis of wood, cellulose, lignin, and coal in an attempt to arrive at a conclusion regarding the interrelationships between these substances. Interpretation of

his analyses led Gillet to propose a generalized formula for coal based on cyclization of the lignin chain structure into a large cyclic unit (63, 64, 65).

In an excellent summary of the status of knowledge regarding the origin of coal, Fuchs (62) has pointed out the importance of hydrolytic processes in decomposing fats, carbohydrates and proteins, the products of which are biologically utilized, to leave as a residue insoluble carbon compounds derived for the most part from lignin, to a lesser extent from resins, waxes, and fatty acids, and to only a slight extent from condensation products of sugars, amines, and phenols. The accumulation of residual material is, as Fuchs notes, not too different in elementary composition from lignin.

Studies of the composition of peat show that material to contain a wide variety of original and partially degraded plant constituents. Theander (144) isolated and identified uronic acids, pentoses, methylpentoses, galactose, glucose, mannose, arabinose, xylose, and rhamnose from sphagnum peat. Brunette and co-workers (25), in a series of studies on the peat bogs of Quebec, showed the material to contain about 7–10 percent hemicellulose, 6–7 percent bitumen, 5–10 percent cellulose, 29–49 percent humic substances, and 7–17 percent lignin. These analyses are significant in demonstrating that the cellulose and lignin residues of the contributing plants decrease as the humic constituents increase. Interpretation of titration curves for the alkaline extracts from peat soils led Puustjärvi (117) to conclude that the extract insoluble in alcohol (humic acid) was derived from cellulose, was made up of heterocyclic furan rings, and had the empirical formula $C_{15}H_{21}NO_4(COOH)_4$, while the extract soluble in alcohol (hymatomelanic acid) was derived mainly from lignin, contained benzenoid structures, and had the empirical formula $C_{65}H_{79}N_2O_6(COOH)_{15}$. Failure to identify in high-rank coals most of the simple compounds that are known to occur in peat attests to the rapidity with which these compounds are decomposed and lost or diagenetically incorporated into the general coal structure. This point was noted by Breger and Whitehead (22) who, using vacuum differential thermal analysis, were able to trace the thermogram for lignin through peat, where it was thought to be masked by a variety of partially degraded plant components, and then into lignite and coals of higher rank.

The present consensus is that, although lignin is probably the major contributor to coal, the role of cellulose and related substances is not well understood. It is conceivable that cellulose may decompose to produce chemical intermediates, which then react to form new materials microscopically recognizable only as gels, or which disappear through interaction with lignin residues or humic substances produced from them (5).

The relationships of plant constituents to each other and to their particular depositional environment have been accorded considerable attention in recent years. It is reasonable to expect that such diverse substances as resins, fats, waxes, lignin, and cellulose should undergo different chemical conversions depending upon their mode of burial. Besides, environmental factors leading to chemical reactions such as oxidation, reduction, and hydrolysis are temperature-, pressure-, and time-dependent. Varying rates of decomposition for any

particular suite of substances could, therefore, result in different admixtures of end products, depending upon their history.

The importance of aerobic processes in the early stages of coalification has been a subject for much discussion. The chemical effects of oxidation are not always easy to recognize inasmuch as they may be manifested by decrease in the hydrogen content of the reacting material rather than by an increase in its oxygen content. However, Schopf (125) suggested, based on a study of fungal remains and a consideration of depositional environments during various geological times, that aerobic decay was probably less important during the accumulation of Paleozoic peat than during the accumulation of later peat deposits.

Study of variations in coalified logs has indicated the importance of depositional environment on the composition of the product (21). The importance of selective and localized chemical or biochemical changes in the formation of excellently preserved long-fibered fusinite has been pointed out by Marshall (103).

That the composition of wood is a factor in its degradation can be judged from the data for deeply buried fossil material being recovered in Byelorussia (136). The high resin content (17–22 percent) of this wood has apparently protected it from decomposition. The relative effects of marine and nonmarine environments of decomposition on the coalification process have also been examined in some detail (90).

The importance of microorganisms in the initial or biochemical stage of coalification is now a generally accepted fact. Fischer (51) recently noted the importance of bacteria of the chromogene and fluorescent types in the decomposition of lignin, a significant observation in view of the previous report by Lieske and Hofmann (97) on the occurrence of these organisms in brown coal. Schwartz and Müller (131) confirmed the earlier work and also reported the consistent occurrence of fluorescent bacteria in open-pit brown coal mines. There are many organisms capable of attacking and destroying cellulose under both aerobic and anaerobic conditions (14).

One of the as yet unsolved problems of the biochemical stage of coalification is concerned with the relationship of brown coal to the peat-lignite-hard coal series. As pointed out by Mackowsky (100), one opinion has it that brown coal and bituminous coal have been formed by different processes, the former through a predominantly reductive process and the latter through a predominantly oxidative process.

Biochemical mechanisms promote the degradation of plant debris to the humic substances that serve as the progenitor for coals of higher rank, but there is little or no evidence that bacteria play any appreciable role in the second or dynamochemical stage of coalification. The difficulty in sampling coal for bacteriological examination (131) has hampered this type of study, but it has long been known that coals of both low and high rank will support only limited bacterial cultures with difficulty. Bacteriostatic and fungistatic substances occur in increasing concentrations going from peat to lignite to subbituminous coal (44, 45, 92); the phenolic character of the humic substances may in itself be sufficient to inhibit bacterial growth.

Besides bacteria, heat and pressure have been proposed as alternate sources of energy for the conversion of humic substances into high-rank coals. One of the oldest attempts to explain coalification was that by Hilt (79) who hypothesized a correlation between the depth of a coal seam and its increased carbon content. In two very significant papers, Trotter (152, 153) noted a lack of any such relationship in several coal fields.

An interesting approach to coal metamorphism was made by Szádeczky-Kardoss (142) who compared diagenetic changes in clays and other rocks with those for coals. Basing his calculations on maximum temperatures for coalification taken from the literature, he derived a relationship in which an increase in temperature of 1° C was equivalent to the application of a pressure of approximately 33 atmospheres.

Other attempts to relate pressure to increase in rank led R. and M. Teichmüller (143) to conclude that pressure is effective in changing the rank of coal only when it is transformed into the heat of friction. That shear forces are important in the formation of bituminous coals and those of higher rank has long been suggested (93, p. 37), but it is not known if heat accompanying the shearing action, as suggested by the Teichmüllers, or the action itself is the important factor in bringing about the chemical changes. In view of the fact that thermal treatment of coal (155) does not lead to changes in composition falling consecutively on the normal coal curve (132), it would appear that the application of shear force is more important than the effects of any accompanying evolved heat. In this respect, Bridgman (23) reported that the application of shear to various organic substances under high hydrostatic head (50,000 atmospheres) caused them to undergo unusual transformations. In particular, Celluloid detonated, and rubber, wood, and paper changed to "hornlike substances." Breger (13) has also reported that on shearing lignin maintained at 100° C and under a load of 1,655 atmospheres, the methoxyl content of the sample was reduced by approximately 0.5 percent as a result of the piezochemical action.

The effects of high pressure on coals have been investigated by several workers in recent years (148, 149, 150). Application of loads of 10,000 kg/cm² to dry, powdered brown coal resulted in slight changes attributed to pressure-induced decomposition of pyrite, and to changes in the quantity and quality of the extractable bitumen. On pyrolysis, the pressurized coals yielded less tar and more coke than untreated coals. Dulhunty reviewed geological factors in the metamorphic development of coal (40) and described an apparatus in which coal samples can be subjected to a compressional force up to 25,000 lb/sq. in., a pressure considered equivalent to burial of 20,000 to 27,000 feet (41). Results of studies with this equipment have not as yet been reported.

X-rays have been used to study the effects of pressure in the metamorphism of coal (118). Loads of 20,000 kg/cm² were reported to reorient the carbon lattice, and it was concluded that bituminous coal, under pressure, is converted into a liquid system with simultaneous destruction of side chains. Here pressure is presumed to bring about chemical changes that permit rotation of the lattice and the development of anisotropy in the coal.

In a detailed study of coal from a single seam, Civran and Petrascheck (31) reported that weak tangential pressure, applied under geological conditions, results in an increase in carbon content and coke for the xylite, decrease in cellulose even in the initial stages of coalification, increase in humic acid and humins, and decrease in lignin. Although these experiments point toward shear force as a possible source of energy for the metamorphism of coal, more detailed laboratory and field investigation will be required for confirmation of the relationship.

The influence of thermal energy in the metamorphism of coal has been difficult to define. Where dikes cut coal seams, alteration of the coal is localized to zones up to about one foot on either side of the intrusion (32). On the other hand, the effectiveness of prolonged, low-level heating on the coalification process has not yet been evaluated (115). Although heating coal does not, as has already been noted, result in normal rise in rank, change in rank is, nevertheless, a chemical conversion, the rate of which is temperature-dependent.

As noted by Petrascheck (115), there is no simple and exact proportionality between overburden to which coal is exposed and its rank, so that besides depth of burial and its accompanying increase in temperature (as well as differences in original substances) other influences, such as faulting, must also be effective in the metamorphism of coal.

PHYSICAL AND CHEMICAL STRUCTURE OF COAL

The last decade has witnessed a major "break-through" in understanding the chemical nature of coal. In part this has been made possible by the development of new analytical techniques, and in part by new and occasionally novel approaches to studies of the constitution of coal. Several important investigations that have provided key information are summarized below:

Statistical Analysis.—The graphical technique employed by van Krevelen (155) for plotting data for coals and related substances on atomic O/C vs. H/C charts has aided significantly in understanding the chemical processes involved in coalification. This clever and useful method for relating data has been of great value in studies of a wide variety of naturally occurring carbonaceous substances (15). Based on data for the elementary analysis of a coal and its density at 20° C, van Krevelen and Chermin developed calculations by which to determine the percent of carbon in a coal that is associated with aromatic structures (156).

Reflectivity.—Reports by Seyler and Edwards (133) that reflectivity measurements indicated the grouping of hard coals into nine stepwise classes have led to considerable independent study by other workers (83, 99). Although other investigators have not as yet been able to reproduce Seyler's nine discrete steps, their work has led to improved methods for studying reflectivity, a useful property of coal for its classification.

Density.—The density of a coal is dependent upon its pore structure. Numerous measurements of true and apparent density, using helium, methanol, water, n-hexane, and benzene were carried out by Franklin (59) who reported

the relatively slow penetration of the latter two liquids owning to their large molecular diameters. Similar detailed studies by Mertins (106) led to conclusions regarding the colloidal structure of various coals, i.e., micellar size, shape, and packing. Dryden (39) very effectively correlated data on densities to explain the minimum in the densities of coals having carbon contents between about 85 and 89 percent (82).

Infrared Absorption.—Infrared absorption is among the newest of the analytical techniques that have been applied to study of the structure of coal. Many workers have examined thin sections of coal, vitrain isolates, and samples mulled in Nujol or pelletized in potassium bromide (24, 61, 158). Although the complexity of coal structure makes interpretation of the absorption spectrum difficult, certain structural features such as substituted phenyl rings, carbon-hydrogen bonding, and hydroxyl groups stand out clearly. The occurrence of carbonyl (>C=O) groups has been questioned by different investigators (9, 158), and a number of absorption bands have been assigned to the presence of specific aromatic and hydroaromatic structures. Recently Friedel (60) explained the color of coal, its infrared, visible, and ultraviolet absorption characteristics, and other properties on the existence of free radicals. The continuing application of infrared spectroscopy, along with other new techniques such as nuclear magnetic resonance, offers great promise toward a better understanding of the relationship between the chemical structure and the physical properties of coal.

X-ray Diffraction.—Whereas infrared absorption provides evidence for the chemical structure of coal, X-ray diffraction studies have provided detailed information on the sizes of the aromatic clusters and their packing. On the basis of combined infrared and X-ray studies, Brown and Hirsch (24) proposed a model for the colloidal structure of coal as a guide to additional work. Siever (134) also studied the relationship between X-ray diffraction and rank.

Differential Thermal Analysis.—This technique has been applied with considerable success to study of the gross chemical structures of coals and related substances (22, 66, 88, 91). Although the method is difficult to standardize because of the large number of variables (33), satisfactory comparative studies have been made of the origin, chemical structure, and metamorphic stages of coal.

Oxidation.—Study of the controlled effects of oxygen has provided data, based on the isolation or properties of the products, on the chemical structures that occur in coal. Nitric acid (89), gaseous oxygen (81), and anodic oxidation (7) have been employed in extensive studies; coal structure has also been investigated by means of comparative studies of the effects of oxygen on phenol (165). A number of important compounds have been prepared and characterized in these studies showing that benzene, toluene, and naphthalene nuclei, or larger systems, are actually present in the structures of bituminous coal. The commercial possibilities of polycarboxylic acids prepared from coals, and their decarboxylation products, have also been considered (47, 58). The isolation of lactones during the oxidation of coal led to the suggestion that these structures are intermediates formed during the course of the reaction (48).

Hydrogenation.—Hydrogenation of coal to produce liquid fuel has been studied extensively (46), and during the past few years mild reduction has been used to investigate the structure of coal. Low-rank coals have been converted to liquid fuel in high yield (87 percent) (6), or have shown improved coking qualities on hydrogenation (95). Methods for the characterization of functional groups have been developed (67), and a large number of constituents have been isolated from hydrogenated lignite (123).

Extraction.—Interest in the production of a montan wax or substitutes for it led to a number of studies on the extractability of wax from low-rank coals by particular solvents. Among the solvents studied, benzene-alcohol mixtures or butanol were found to be most effective. Considerable data have been reported (69, 96, 112) in which the properties of waxes extracted from lignites were compared with the properties of montan wax. It is not known if any wax has been or is being extracted commercially.

Solvent extraction of bituminous coal as a step in the study of its chemical composition and colloidal structure has been studied in great detail by Dryden (38). The dispersing and dissolving actions of ethylenediamine have been exhaustively investigated; molecular weights of pyridine extracts have also been determined (164).

Numerous other techniques have been employed for study of the physical properties and chemical structure of coal. Notable among these are refractivity (128), conductivity (129), elasticity (127), dielectric constant (72), thermal expansion (130), and diffusion (166). Much of this work has been summarized by van Krevelen and Schuyer in their recent book (157). Of particular interest is the attempt to relate hydrogen, oxygen, density, refractive index, and volatile matter of coal macerals to their carbon content, thus showing the effects of diagenesis on the chemical composition of micrinites, exinites, and vitrinites (157, p. 234–243).

COMPOSITION OF COAL

The role of coal in the geochemical cycle of carbon has been considered in great detail by Borchert (11). Trofimov (151) reported bitumens, petroleum, and coal to have high C^{12}/C^{13} ratios compared to limestones, dolomites, or carbonate minerals. Wickman found, on study of coals of various ages, that the youngest samples had the highest ratios (163). In no case was Wickman able to establish an influence of metamorphism on the isotopic ratio. A wide range in values for coals of various ages has since been shown (86) and explained on the basis of variations in the composition of the atmosphere and hydrosphere during geologic time. The work of Craig, who reviewed the methods used and compared data for many types of organic and carbonate rocks, also led to the conclusion that there is no correlation of C^{12}/C^{13} ratio with age for coals and fossil wood (34).

As pointed out by Francis (56), most attempts to classify coal have been based on average ultimate analyses and disregard for the fact that coal is a heterogeneous substance. Although this defect is readily apparent, the simplicity of classification schemes based on carbon and hydrogen content, and the

utility of such methods in commercial practice, has led to their continued use. Charts of the type prepared by Seyler (132) combining ultimate analyses and engineering data are extremely useful but are based on average data that may differ somewhat for coals from various sources (140). This type of classification, depending upon ultimate analysis or empirical measurements, has been extended (70) and has also been applied to the subdivision of brown coals (98). The development of scientific classification of coal that will also be of practical use is dependent upon the accumulation of data for macerals and constituents isolated from coals of various ranks (56, 157; p. 234–243).

Extraction of coal for recovery of substitutes or montan wax has already been mentioned. In some coals such as those from Utah, coal resin occurs in discrete stringers and coarsely disseminated particles, and can be isolated by sink-float techniques. This resin, nearly pure hydrocarbon, has been recovered on a commercial scale (1). Lignites from Austria (154), Russia (43), and India (159) have also been reported to contain easily separable concentrations of fossil resin. In the case of the Austrian samples, the resin, derived from *Pinus succinifera*, is very complex consisting of resinols, acids, and unsaponifiable substances.

The mineral content of coal continues to be of major interest. Many studies of mineral content and distribution have been reported, and new or improved techniques for its study, such as radiography (101), electron microscopy (105), and X-ray diffraction (111), have been employed with varying degrees of success. Using these techniques, kaolin, muscovite, pyrite, marcasite, α-quartz, gypsum, calcite, dolomite, anatase, and apatite have been recognized. Float-sink separations have been used to up-grade certain coals, and in the case of that from the Kuznetsk basin, gravities over 1.500 led to the isolation of high-ash fractions that were predominantly durain (71). Beyond these studies, the greatest effort of the past decade has been applied toward improvement of calculations for correlation of mineral species and ash content. An extensive review on mineral matter in coal by Venter and Coppens summarizes much of this work (162).

Much attention has been accorded to the geochemical principles underlying the formation of certain minerals in coal. As one example, Hoehne (80) studied the occurrence of clay concretions important as a marker horizon in Westphalian coal seams and concluded the material not to be derived from volcanic tuff as previously supposed. Rather, Hoehne concluded that the concretions were formed from silica-alumina hydrogels in the peat swamp in the presence of humic acids. Also, quartz grains thought to have been introduced through sedimentation were shown to have coal inclusions and to have formed from a gel. Manger (102) explained the formation of marcasite in brown coal on the interaction of solutions from sulfur-rich coal with those from adjacent iron-rich marine sediments. The precipitation of iron in peat soils was found to occur in deeper layers where the carbonate forms at relatively high pH (116).

Extensive studies of minor elements associated with coals have been conducted during recent years. Considering the tremendous tonnage of coal mined annually and the concentration factor in reducing coal to its ash, it is under-

standable that coal ash would provide an important source for any easily recoverable element of commercial value.

Hashimoto (74) and Inagaki (84) concluded there to be no correlation between the distribution of elements in vitrite and durite. In continuation of the studies initiated by Goldschmidt (68), Headlee and Hunter (78) analyzed the ashes from 596 samples of coal for 38 elements and found Na, K, Rb, Ca, Mg, Si, Cr, and Mn to be present to a lesser extent than in the earth's crust. On the other hand, Li, Sr, Ag, As, Bi, B, Ga, Ge, La, Hg, Pb, Sb, Sn, Zn, and Zr were enriched, compared to the earth's crust, by factors of 10 to 185. In similar studies of 27 elements in the ash of 319 samples of low-rank coal from five localities, Deul and Annell (37) reported no general enrichment over occurrences of the elements in coals from other areas. Some enrichment of B, Ba, and Sr was noted in all the samples, but of particular interest was the fact that lignite from Milam County, Texas, was found to contain unusually high concentrations of Sn, Cu, Zr, B, Ba, and Sr. Hawley (75) found coal from Nova Scotia to be enriched in Ba, Sr, Mn, As, and Pb, but to have lower than normal values for Be, B, V, Cr, Co, Ni, and Mo. Besides these general studies, the occurrences of a number of elements in coals and coal ashes have been studied in detail. These elements are listed below:

Germanium.—The post-war development of transistors sparked the search for sources of germanium. Based on early reports that certain coals were particularly enriched in this element, considerable reconnaissance for germaniferous coals was conducted in many countries. Analysis of 200 British coals led Aubrey to report an average content of 7 ppm of germanium, the same order of content as in most sedimentary rocks (2). Similarly, Belgian coals contain 1–10 ppm (121). Most analyses for germanium are reported on the basis of the concentration of the element in the coal ash. Here the important factor of ash content and secondary enrichment during ashing is not always easy to evaluate. In any case, the following average concentrations of germanium in coal ash have been reported: British, 50 ppm (3); Canadian, trace to about 1,000 ppm (55, 76); Czechoslovakian, 1–10 ppm (135); Japanese, 100 ppm (85); and American, up to 2,000 ppm (77, 138).

The association of germanium with most coals is probably secondary as indicated by the fact that concentrations are frequently reported to be top or bottom preferential within a seam (76, 77, 87, 138). Many samples with unusually high concentrations of germanium have also been found. Stadnichenko and co-workers (137) reported the ash of lignitic remains of *Cupressinoxylon wardi* from the District of Columbia and vicinity to contain 2–9 percent germanium, more than 10,000 times the average content of the element in the earth's crust; Breger and Schopf reported up to 4 percent germanium in the ash of coalified logs from Devonian black shales (20). The mechanism for concentration of germanium by coal is not known; coprecipitation with aluminum humates in analogy with aluminum (122), or chelation with humic material in analogy with uranium (20) have been suggested.

Analysis of coal ash, flue dusts, and gas liquors derived from power plant operation and carbonization processes has shown that the germanium distributes itself among the coke, tar, gas liquor, and even crude naphthalene prod-

ucts (54, 113). Failure to obtain selective concentration of the element in any particular fraction has presented an effective barrier to recovery of germanium from these operations on a commercial scale.

Uranium.—The intensive search for new sources of uranium led to the discovery of low-rank coals containing appreciable percentages of that element (36). In some instances the uranium content of the coal is sufficiently high to warrant its consideration as an ore rather than as a fuel (26). The occurrence of uraniferous coals is geographically widespread (Hungary, 53, 141; Germany, 35; France, 124) but apparently limited to lignites and subbituminous coals. Numerous studies of the uranium content of bituminous coals of the eastern United States have shown insignificant percentages of the element; in western states the percentages are somewhat higher but too low to be of interest from the standpoint of recovery.

The capacity for coal toward uranium is very high (109), and several investigations have been carried out to determine the means by which coal absorbs and retains the element. Study of a uraniferous lignite from South Dakota led to the conclusion that the uranium was retained in the form of an organo-uranium complex soluble at a pH less than 2.18; only 1.2 percent of the element was found to be retained by ion exchange (19). Szalay also concluded that treatment of Hungarian brown coal at pH less than 3 was necessary to liberate the uranium, but suggested adsorption as the mechanism by which the element was retained (141). Petrographic study of uraniferous coals failed to establish any correlation between uranium content and any coal component, but did indicate a relationship between high values of uranium and samples rich in humic matter (126).

Sources for uranium associated with coals may vary with geological environment. Overlying volcanic tuff has been suggested as the source in the case of lignite of South Dakota (36), but any eroding granite or low-grade uraniferous marine shale could also supply uranium for secondary concentration by coal (17).

The absorption of uranium by coalified logs of the Colorado Plateau has been studied in detail (21) and found to be accompanied by formation of organic sulfur compounds and by radiochemical dehydrogenation. The mechanism for accumulation of uranium in these logs is thought to be similar to that proposed for the massive lignites and subbituminous coals (18). Following absorption of uranium, however, reduction of the uranyl (UO_2^{++}) ion to uraninite apparently occurred (120).

Besides coalified wood, uranium of the Colorado Plateau is also associated with a black, lustrous carbonaceous material in which no cellular structure has been identified. There has been much speculation on the origin of this material, but recent evidence indicates that it was derived from low-rank coalified wood by extraction and subsequent precipitation (16).

Besides the commercial potentialities of high-grade uraniferous coals, those with low percentages have been used in the correlation of coal seams (29).

Sulfur.—Commercial interest in the sulfur content of coal has led to the development of new improved analytical techniques. In spite of continuing

work, however, determination of forms of sulfur in a coal leaves much to be desired.

A number of coals with high organic sulfur contents have been studied in some detail. In the Assam coal from India, sulfur occurs in the form of thiols, sulfides, disulfides, and sulfur-ring compounds (30). Kreulen (94), and Hadzi and Novak (73) independently studied the properties of the high sulfur coals of Istria. These coals containing 8.5 to 11 percent organic sulfur show odd properties, with volatile matter, tar yield, and reflection indicating low rank, whereas coking index, heat of activation, ignition temperature, and bed moisture indicate high rank. The Raša (10.5 percent organic sulfur) and Timov (8.5 percent organic sulfur) coals have essentially the same properties but differ from the Sečovlje coal which, with nearly the same sulfur content as the Raša coal, has comparatively poor swelling and coking properties. Neither the origin of the sulfur nor its form in the coal is known.

Marshall and Draycott (104) investigated the high organic sulfur Tangorin coal of Australia (4.8–5.0 percent organic sulfur) and concluded the sulfur to be located in the vitrinite, which also has a high (5.8–6.6 percent) hydrogen content. The origin of the sulfur is thought to be related to an unusual plant assemblage that contributed to the coal.

Among the examples of high organic sulfur coals are the uranium-bearing coalified logs of the Colorado Plateau. Values of over 12 percent have been recorded with a maximum of 13.1 percent (21), the highest organic sulfur value for coal or coalified wood that has been noted. In this sample there is evidence that sulfur, probably as hydrogen sulfide, reacted with the coal under conditions of mineralization to yield organic sulfur structures.

Phosphorus.—Feigel'man (49) identified a relationship between petrographic types and phosphorus content in a coal from central Asia. Bright coal was found to contain 8 to 10 times less phosphorus than semidull coal; no correlation was observed between ash content and phosphorus.

Vanadium, Chromium, and Nickel.—Interest in these elements has continued but has not led to much new information. Reynolds (119) found vitrainlike material in the roof and floor of certain coal seams to be enriched in the three elements, and Stadnichenko (137) reported the ash from germaniferous lignite to contain from 0.7 to 5 percent vanadium, and from 0.1 to 0.8 percent chromium. Aside from these unusually high concentrations, Butler (27) found Spitzbergen coals to carry no unusual concentration of the elements (10–1,000 ppm).

Arsenic.—Study of the arsenic content of wood (108) revealed such low percentages (1.1×10^{-5} to 5×10^{-6}) that Minguzzi and Naldoni suggested the higher arsenic content of coal to be of secondary origin. Duck and Himus (42) concluded that most of the arsenic of coal is in the form of arsenopyrite; partial extraction of arsenic with dilute nitric acid, however, indicated the possibility of some organically combined arsenic. On combustion approximately one half of the arsenic is retained by the ash.

Rare Earths.—These elements have been identified in coal ash by cathode luminescence (110) when they are present in percentages too low to detect by other techniques. No quantitative determinations were reported.

Rare Gases.—Patteisky (114) analyzed mine gas in the Ruhr area and found it to contain 10–20 percent methane, 14–20 percent carbon dioxide, 65–75 percent nitrogen, about 4 percent helium, and 0.1–1.2 percent neon. Small percentages of argon and krypton were also found. A relationship between helium and nitrogen was recognized but none between helium and carbon dioxide. This helium-rich mine gas has been suggested as a source for that element.

Beryllium.—Stadnichenko, Zubovic, and Sheffey (139) studied the beryllium content of ash prepared from 1,123 samples of American coals and reported an average value of 4.5×10^{-3} percent. This value is more than 20 times the abundance of the element in the lithosphere.

DISCUSSION

Accumulation of knowledge about the chemical structure, composition, and physical properties of coal has progressed very rapidly during the past 10 years. The development of new analytical techniques has permitted a deeper insight into the structure of coal and a better understanding of its potential as a chemical raw material. Much credit for this progress must be attributed to the team scientific approach in which geologists, petrographers, chemists, and physicists have worked together, each contributing a share in a borderline field of investigation too broad to be handled solely by those in any one particular science. The success attained by this cooperation points to the need for its continuation and expansion as an investigative technique, especially in view of the expanding body of scientific knowledge.

Consideration of recent progress indicates the desirability of a number of geochemical studies some of which are noted below:

(A) The source of energy for the conversion of humic materials to hard coal has still not been demonstrated. Geological evidence points toward shear under pressure, but aside from several inconclusive laboratory experiments, there has been no directed effort to determine the effects of pressure on coal and its precursors. Examination of this problem offers more than a solution to the diagenesis of coal, for the effects of shear on organic substances is a field that has been dormant for too many years.

(B) Major attention has been directed toward study of bituminous coal, and comparatively little effort has been given to chemical study of peat, and especially lignite, during the past decade. The enormous resources of both peat and lignite, the reactive chemical character of the substances, and the fact that lignite is already being mined and commercially utilized for fuel, make it appear likely that by-products could be produced inexpensively if more were known about chemical structures and composition. Study of lignites, in particular, offers promise not only of geochemical knowledge regarding the formation of coal, but for the utilization of the coal in the synthesis of chemicals.

(C) There have been many general and a few specific surveys of the minor elements in coals. Although considerable information on geochemical processes of enrichment has been accumulated, much more work in this field is required to determine the affinity of humic substances for various elements

and the geochemical behaviour of various elements at different pH values in the presence of one another and of humic substances. In many instances concentration of an element by coal is secondary and dependent upon a source of supply. It would appear useful, therefore, to survey the elemental concentrations of coals in particular environments such as those where the coals are able to accumulate elements liberated by eroding shales or igneous rocks.

(D) Much more research is required into the chemical composition of macerals isolated from coals of varying rank. Techniques for isolation of macerals in sufficient quantity for detailed analysis need development, and some ingenuity in this field will be required. The accumulation of data for macerals will permit closure of a missing link between the visual observations of the petrographer and the chemical composition of the coal constituents, and permit development of a classification for coal useful both scientifically and economically.

There has in the past been considerable difficulty in communication of ideas between coal petrographers and coal chemists. Fortunately, petrographic terminology is now in the process of review on an international basis. However, until the constitutional relationship of samples of the same maceral can be demonstrated, the descriptive observations of petrographers, which are subject to differing interpretations, will have no common denominator for comparison. As application of coal petrography for industrial purposes becomes more widespread the need for this type of work becomes more pressing.

Although it is not the function of this paper to review advances in industrial techniques for the utilization of coal, it is clear that developments in this field and additional knowledge regarding the composition of coal will together lead to better and diverse products. Achievements of fundamental studies of the past forty years are finally being recognized by industry. It is hoped that as industry continues to realize the value of this work, commercial research and development will, in recognition of a good investment, expand the activities now confined almost entirely to government and academic laboratories.

U. S. Geological Survey,
Washington, D.C.,
April 19, 1958

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Economic Geology
Vol. 53, 1958, pp. 842–853

OCCURRENCE OF GIBBSITE ON THE ISLAND OF KAUAI, HAWAIIAN ISLANDS

AGATIN T. ABBOTT

ABSTRACT

Under conditions of a sub-tropical climate and approximately 100 inches of rainfall annually, plagioclase feldspar in the olivine basalt flows of the Koloa series alters directly to gibbsite. Four stages of weathering are outlined. Between stages two and three there is a large and abrupt increase in the percentages of alumina and iron and corresponding impoverishment in silica, calcium, and magnesium. In the fourth stage some of the alumina becomes mobilized, migrates through the leached rock and is redeposited as filling material in fractures and cavities. Some of these concentrations weather out of the lateritic soil and strongly decomposed rock in the form of irregularly shaped nodules of gibbsite.

INTRODUCTION

General Statement.—The mineral gibbsite, aluminum trihydrate, occurs on the island of Kauai and elsewhere in the Hawaiian Islands, and may exist in sufficient grade and quantities to provide a source of aluminum ore. This paper describes an alteration sequence from the basaltic source rock to the gibbsitic end products. The gibbsite occurs as nodules, agglutinated particles, and disseminated grains in the lateritic soil and in strongly altered basaltic rock as a decomposition product of plagioclase feldspar and, to a lesser extent, other aluminum-bearing silicates including melilite and nepheline. On Kauai, gibbsite is the result of thorough surface leaching of rocks comprising the Koloa volcanic series (11, p. 85–89) which Macdonald (7, p. 1558) described as including olivine basalt, "linosaite," picrite-basalt of the mimosite type, "ankaratrite," nepheline basanite, nepheline basalt, melilite-nepheline basalt. The weathering sequence is determined from olivine basalt, which is considerably more abundant in the area studied than the other types.

Location and Accessibility.—The island of Kauai is the northernmost of the main islands in the Hawaiian archipelago (Fig. 1) and lies 120 miles northwest of Honolulu, which is on the Island of Oahu and is the largest city in the Territory. Flying time from Honolulu to Lihue, which is the principal city on Kauai, is approximately 30 minutes.

Kauai possesses a rudely circular outline, is 555 square miles in area, and rises to a height of 5,170 feet above sea level at the summit of Mt. Waialeale. Deeply incised streams radiate from the summit and make travel extremely difficult in the higher elevations.

In the lower elevations along the eastern coast gently seaward sloping Koloa volcanics afford easy access. It is in these areas that most of the gibbsite occurs. (Fig. 1). A good paved highway follows the coastline. Upland areas may be reached along county access roads or along privately

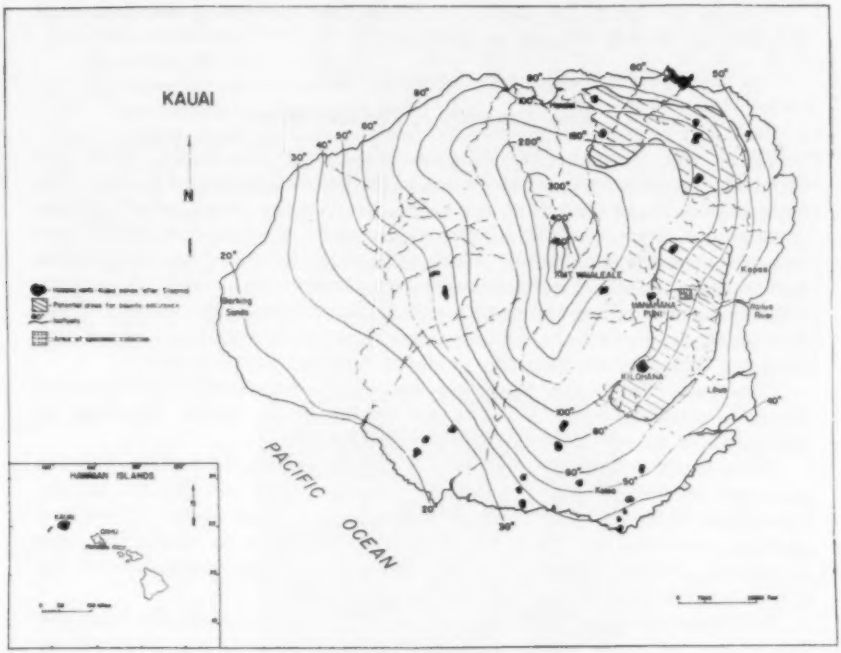

FIG. 1. Location, outcrop and rainfall map.

owned plantation roads up to an average elevation of 600 feet. Above this level travel is by Jeep or on foot.

Climate and Rainfall.—Because the island lies within the belt of northeasterly Trade Winds it is favored by a mild, sub-tropical climate. Rainfall varies directly and dramatically with elevation and also with position on the island relative to the prevailing northeasterly Trades (Fig. 1). Along the southwest coast in the vicinity of "Barking Sands" annual rainfall is less than 20 inches. On the north coast rainfall is about 90 inches. At the summit of Mt. Waialeale, which carries the distinction of being one of the wettest spots on earth, annual precipitation reaches 450 inches or more.

Acknowledgments.—My sincere appreciation is extended to Reynolds Mining Corporation of Little Rock, Arkansas, and to its President, Mr. Walter L. Rice, Vice President, Mr. R. H. Zeglin and to Mr. R. W. Roley and Mr. B. A. Randall, assistants to Mr. Zeglin. It was through the auspices of this company that the collection of data and the permission to publish this paper was made possible.

For his pioneering work in Hawaiian soil studies, the writer is indebted to Dr. G. Donald Sherman, Chairman of the Department of Soils and Chemistry, University of Hawaii.

Thanks are due to Dr. Gordon A. Macdonald for reading the manuscript and offering several valuable suggestions.

GEOLOGY

Brief Summary of Previous Work

Hinds (6), Stearns (11), Macdonald (7) and Macdonald, Davis and Cox (8), are the principal contributors to the general geology of Kauai. The main volcanic mass consists of two parts; the Waimea series, which consists of flows and ejecta from the original cone, and the Haupu series, which consists of caldera-filling material. These rocks are separated by a great erosional unconformity from later flows and effusive rocks that were erupted from vents aligning north–south on the eastern and southern sides of the island. These later flows are termed the Koloa series. It is upon surfaces of the Koloa volcanics that deep leaching has produced lateritic, gibbsitic soils.

The age of the island of Kauai is considered by Wentworth (15) to be late Tertiary, probably Pliocene. The age of the Koloa series, according to Macdonald et al. (8) is Pleistocene through Recent.

On a world wide scope Harder (4) lists several major bauxite deposits that were formed in Quaternary time. He also points out that the bauxite deposits of India are derived from basalt of the Deccan flows. There is a geologic precedent, therefore, for the gibbsitic deposits on Kauai from the standpoint of time or origin and also from the general composition of the original source rock.

Determination of the high alumina content of certain soils in the Hawaiian Islands and the identification of gibbsite by X-ray analysis was pioneered by Tamura (13) and Tamura, Jackson, and Sherman (12). Until 1955 there was little active commercial interest shown in this mineral.

After a preliminary examination late in 1955 Reynolds Mining Corporation started an extensive exploration program on Kauai early in 1956. Shortly thereafter, Kaiser Aluminum and Chemical Corporation, Oregon Bauxite Company, and Olin Mathieson Company entered into exploration activities in the Islands. The exploration work continued until the end of 1957.

Weathering Sequence

Petrographic study was made of a suite of specimens ranging in degree of alteration from fresh olivine basalt to the final product of gibbsite nodules. The specimens were collected in the upper Wailua River drainage area, between Kilohana Crater and Hanahanapuni Crater, and represent a vertical sequence of approximately 60 feet.

Megascopic Features

Fresh Rock—Stage 1.—The unaltered parent rock is exposed at water level of the Wailua River (Fig. 2). It is a dark gray, compact, evenly textured, very slightly vesicular, olivine basalt (Fig. 3). It is exceedingly tough and hard. The vesicles are not over 2 mm in diameter. That they

provide avenues for water circulation is shown by the aureoles of moisture that become visible around vesicular openings when the rock is freshly broken.

Moderate Alteration—Stage 2.—Moderately altered rock exposed about 20 feet above the river channel shows marked changes resulting resulting from downward circulation of ground water (Fig. 3). The rock is highly porous. The enlarged openings are irregular or ellipsoidal in shape and might be mistaken for true vesicles, however, it appears probable that they result from leaching and hydration. Care was taken to determine whether the increase in porosity might be due to the fact that the rocks just described belonged to separate flows. Conclusive field evidence shows they belong to the same flow. The rock in this stage of leaching is notably softer than the very fresh rock, and, although it resists well the blows of a hammer, it does not produce the clear ringing tones or the elastic rebound that is imparted to the hammer by the fresh rock. Reddish-orange iron oxide occurs as specks in the dull gray

FIG. 2. Fresh olivine basalt exposed in the channel of the Wailua River.

matrix and as coatings in the cavities. Where the degree of alteration is more intense along fractures and joints, the iron oxide and reddish color become very prominent. Incipient development of spheroidal weathering caused by ground water percolating along fracture zones appears toward the upper part of this rock unit.

Severe Alteration—Stage 3.—The strongly altered rock that overlies the one just described extends upward from about 30 feet above the river channel to the topographic surface and locally attains a thickness of 30 feet. It consists of lateritic clays, strongly altered rock fragments and a few fresh rock cores of spheroidal boulders. The altered rock fragments, which are gibbsitic, contain many cavities estimated in some specimens to comprise 30 percent pore space in the rock. The prominent grayish color of rock in the first and second stages is replaced by red, reddish-orange, and brown. The original fabric of the rock may or many not be preserved, although the constituents of original minerals, with the exception of the black opaques, are entirely

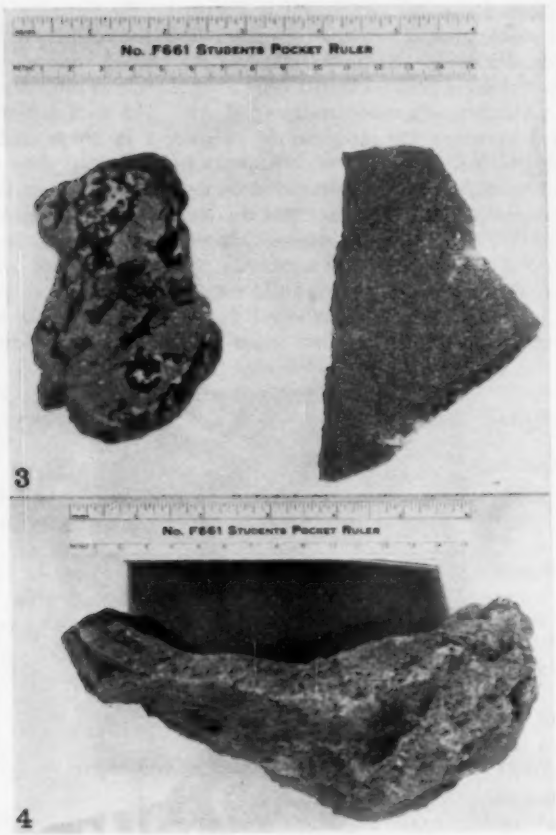

FIG. 3. Fresh olivine basalt, Stage 1 (right). Moderately altered olivine basalt—Stage 2 (left).
FIG. 4. Severely altered olivine basalt. Stage 3. Note concavity of spalled fragments.

removed or replaced. Minute white or yellowish specks in the rock matrix, thin coatings on the interior of cavities, and thread-like, white stringers may occur in this stage. These specks and coatings are identified as gibbsite. The rock fragments are fairly soft but do not crumble in the fingers. The clay component, which comprises approximately 80 percent of the bulk in samples from the severely leached zones, has been termed by Sherman (10) an aluminous ferruginous latosol. The clay fraction carries some alumina, probably as very finely divided gibbsite, however, higher concentrations of gibbsite occur in the coarser material. Reddish brown, gibbsite-bearing rock

fragments that vary in length from ½ inch to 6 inches and are commonly concave in shape occur abundantly on the surface of cultivated ground or just below the surface of undisturbed ground (Fig. 4).

Nodular Gibbsite—Stage 4.—The fourth and final stage of alteration produces lateritic soil and lateritic crusts described by Sherman (9) and also concretionary, nodular, and tubular accumulations of nearly pure gibbsite, which are chalky white and contrast markedly in color from the surrounding reddish soil. A strong tendency for the gibbsite nodules to cling together

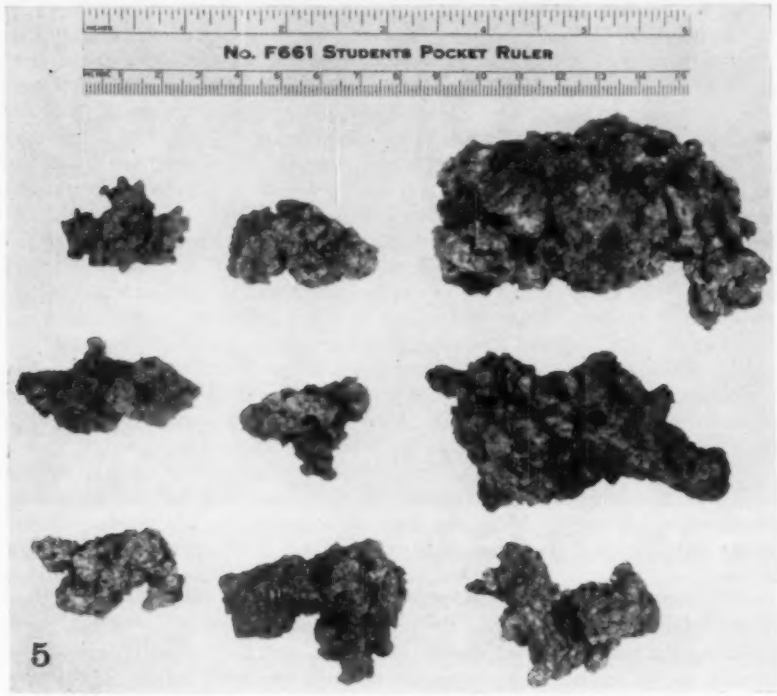

Fig. 5. Nodular masses of gibbsite. Stage 4.

produces grotesque shapes in the clusters (Fig. 5). Some agglutinated masses reach 6 inches in length. Gibbsite occurs in this stage also as elongate stringers generally less than ½ inch in width and of indefinite lengths and patterns. The stringers follow joints or desiccation cracks in the upper soil horizons. Concentric banding in the stringers indicates a filling mechanism.

The freshly broken gibbsite nodules show a greenish gray color on the inside. The outside is generally thinly coated with white, chalky mineral, probably kaolin, which has been formed by the resilication of gibbsite; a

process discussed by Allen (1) Harrison (5) Harder (4) Goldman and and Tracey (3). Specimens of gibbsite of this type may approach 60 percent Al_2O_3. There is little question that the fractures and cavities were filled by lateral or downward migrating, alumina-bearing solutions. There is no evidence of an upward migration of alumina. Gibbsite deposited within open spaces assumed the shape of the openings, some of which are very irregular. No measurements are currently available on distances of migration of the alumina.

Microscopic Description

Fresh Rock—Stage 1.—In thin section (Fig. 6), the unaltered basalt displays distinct porphyritic and intersertal textures. Olivine forms euhedral to subhedral phenocrysts and augite occurs as small anhedral grains between abundant laths of plagioclase. Magnetite–ilmenite grains are present but not in excess. Volcanic glass occurs in the groundmass.

The olivine crystals reach a maximum length of 1.5 mm, are fresh and display the customary curving fractures along which no alteration occurs; nor is there iddingsite or other alteration product around the olivine rims. The irregulary shaped augite grains average about .3 mm in diameter and, like the olivine, show no alteration. Plagioclase feldspar, which comprises about 35 percent of the rock, occurs as euhedral, lath-shaped grains which show no preferred orientation. Most grains are twinned according to the albite law and the twining planes are straight and distinct. The maximum length of the laths is about 1.5 mm. Glomeroporphyritic clusters are fairly common. The composition of the plagioclase is labradorite, Ab44An56. The feldspar is unaltered and contains few inclusions. Volcanic glass, which fills some of the interstices between the crystalline minerals, is clear and unaltered.

The order of crystallization noted by Macdonald (7, p. 1570), namely olivine first, as an intratelluric crystal, then feldspar and then augite is substantiated in this work. Iddingsite does not occur as rims surrounding olivine grains until Stage 2, and then it is apparently a direct product of leaching action.

Moderately Altered Rock—Stage 2.—In this stage (Fig. 7) the olivine shows definite alteration around the rim to iddingsite, and in the central parts and along the fractures to serpentine, iddingsite, and iron oxide. Most olivine crystals, in the second stage, retain the more or less fresh cores. The augite alters partially to epidote, which fills interstices between crystals and coats the walls of newly formed pore spaces and cavities that were noted in the megascopic description. Some epidote is also apparently derived from alteration of the volcanic glass in the matrix. The plagioclase remains virtually unaltered.

Severely Altered Rock—Stage 3.—In this stage profound changes take place in the mineral assemblage. The transition from the mineral assemblage in Stage 2 to that in Stage 3 is exceedingly abrupt. Harder (4) reports that the contact between bauxitic and unaltered rock my be as thin as a knife edge. Figure 8 shows such a contact, in the Kauai sequence although a small crack, .3 mm wide, separates the nearly fresh rock from the gibbsitic laterite. Thin

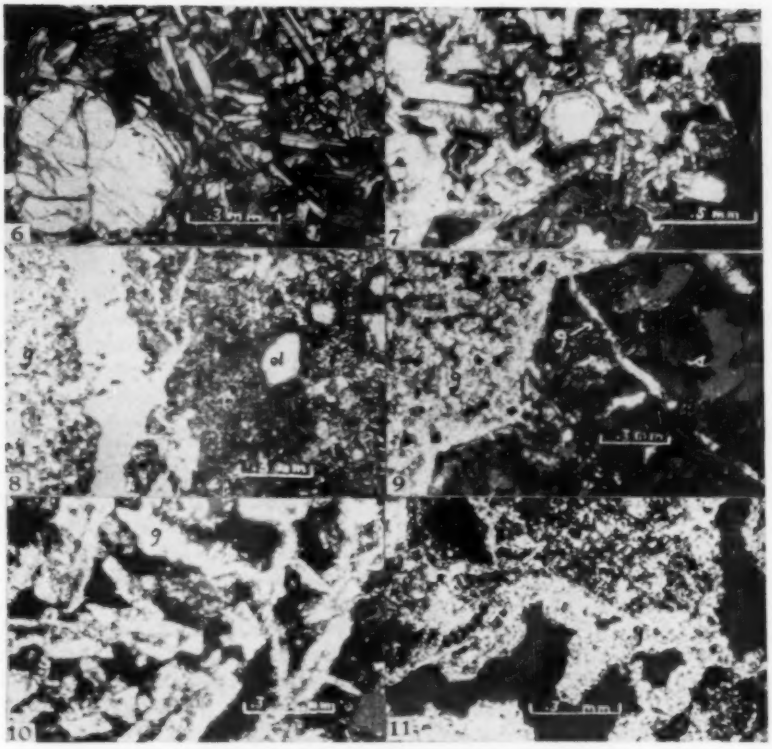

FIG. 6. Photomicrograph, x-nicols. Fresh olivine basalt. Stage 1.

FIG. 7. Photomicrograph, x-nicols. Moderately altered olivine basalt. Stage 2. Note development of iddingsite rims and epidote.

FIG. 8. Photomicrograph, x-nicols. Olivine basalt showing sharpness of contact between nearly fresh rock on right and severely altered rock on left. Stage 3.

FIG. 9. Photomicrograph, x-nicols, showing abundant gibbsite in the matrix and also as a filling in cleavage cracks in iddingsite which is pseudomorphous after olivine.

FIG. 10. Photomicrograph, x-nicols, showing pseudomorphous replacement of plagioclase by gibbsite. Stage 3.

FIG. 11. Photomicrograph, x-nicols, showing the coating of irregularly-shaped cavities by coarse-grained gibbsite.

sections of rocks in this stage of alteration show complete disappearance of olivine. Generally a rim of iddingsite around the former olivine crystal preserves the original shape. The interior of the leached olivine crystal is in part void space, and in part may be filled with serpentine, iron oxide, and iddingsite; the pseudomorph may be criss-crossed with stringers of gibbsite that follow fracture patterns in the olivine and cleavage planes in the iddingsite

(Fig. 9). Augite and epidote are absent from the mineral assemblages in Stage 3. Their disappearance is exceedingly abrupt. The enveloping wave of bauxitization removes the iron, magnesia, calcium, and silica with apparent ease and thoroughness. Some of the alumina in the augite may convert to gibbsite although measurement of the amounts is inconclusive. All plagioclase goes directly to gibbsite without any intermediate kaolin stage such as has been noted in other localities by Allen (2). The plagioclase-derived gibbsite commonly occurs as disseminated, minute flakes throughout the groundmass, which retains only a slight suggestion of original texture. Less commonly, the gibbsite is pseudomorphous after plagioclase; and the lath-like outlines of the feldspar are perfectly preserved (Fig. 10).

In addition to occurring as minute flakes in the groundmass and as pseudomorphs after the feldspar in Stage 3, the gibbsite shows unmistakable evidence of having migrated and been redeposited. Numerous stringers up to .5 mm in width are composed of nearly 90 percent coarsely grained gibbsite (Fig. 12). Cavities are partially, or in a few places, completely filled with coarsely grained gibbsite. Gibbsite-filled fractures that lead into cavities show evidence of being channelways through which the mobilized alumina travelled; and then at some point of time crystallization of the alumina resulted in filling the open spaces (Fig. 11). The migrant gibbsite that has been redeposited is invariably of coarser grain than that which is more or less in place. Gibbsite-coated vugs in the central portions of the stringers are common.

This offers a puzzling situation. The hydrous aluminum oxides are generally considered to be some of the most stable and resistant to leaching action, and yet during the final stages of the leaching process, the alumina moves out to be redeposited in another location, or in some instances may leave the system entirely, while the iron oxides and iron silicates and opaques remain in place. Thiel (14) has demonstrated in the laboratory that microorganisms contained in residual soils are effective in promoting solubility of alumina. He states:

> The results of experimental work by the writer dealing with various groups of ammonifying and sulphate reducing bacteria that are commonly present near the surface in residual soils and rock waste, indicate that through the aid of biochemical reactions there is a conservation of essential constituents, and a very small amount of iron sulphate is suffiicient to produce the liberation of relatively large quantities of alumina.

It is possible that bacteria in the soils derived from the Koloa series are responsible for the liberation and migration of some alumina.[1]

Nodular Gibbsite—Stage 4.—The fourth stage is represented by larger masses of gibbsite up to six inches in length that are formed exclusively by migration and redeposition of the alumina. These larger masses occur as fillings in elongate, swelling and pinching stringers that can be followed in the

[1] While this manuscript was in press W. D. Keller published an excellent paper on the relative solubilities of silica and alumina. He demonstrates that their mobility is dependent on the pH of the environment at the hydrolyzing interfaces of the minerals involved. At pH 10+, both Al_2O_3 and SiO_2 are mobile; at pH 7 to 9.5 Al_2O_3 is immobile, SiO_2 is mobile; at pH 4.5 to 7, Al_2O_3 is immobile, SiO_2 mobility is low. (See Bull. Amer. Assoc. Petrol. Geol. vol. 42, p. 233–245, 1958.)

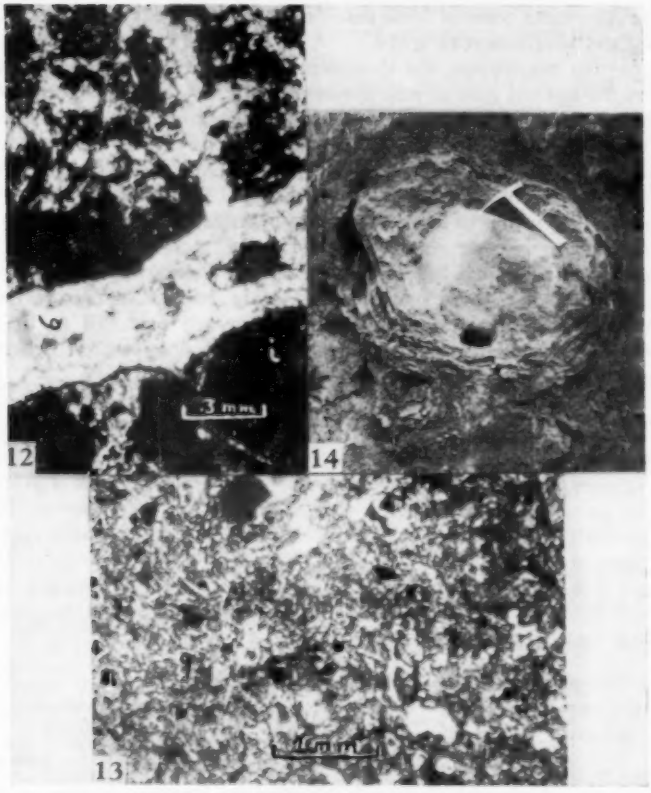

FIG. 12. Photomicrograph, x-nicols, showing coarse-grained gibbsite filling a fracture in the leached rock.
FIG. 13. Photomicrograph, x-nicols. Nodule of gibbsite. Stage 4.
FIG. 14. Spheroidal boulders as exposed in a road cut. Note the sharp contact between the fresh core and the altered periphery.

field for several yards. In thin section the gibbsite appears very pure with the exception of swarms of opaques, probably ilmenite, that persist into this final stage. Hydrous iron oxide, and iddingsite are practically absent. The texture of the gibbsite is intricate and forms scroll-like patterns in a turbid groundmass that is also composed of gibbsite (Fig. 13). Small, open spaces are coated with coarsely grained gibbsite.

Spheroidal Boulders

A special situation of considerable interest and importance in the understanding of the rapidity of leaching in the Koloa flows, is the sporadic occur-

rence of spheroidal cores of fresh basalt near the surface in the zones of severe leaching and laterization (Fig. 14.).

Under the microscope, the sharpness of line between the relatively fresh core and the leached zone is well demonstrated in one section by a phenocryst of olivine 2 mm in length that projects from one zone to the other so that half of the crystal lies in each zone. In the fresh part the crystal, although it shows only slight alteration to iddingsite, is clear and unblemished. In the altered zone less than 1 mm distant the olivine has vanished leaving only a void space containing a few specks of limonite rimmed by iddingsite.

The outer concentric rims of the weathered boulders become detached from the main mass and are incorporated in the soil. Upon cultivation of the pineapple fields, these spalled sections are brought to the surface and compose the abundant fragments of float that are scattered in the fields. Where the ground is undisturbed the float is not visible because it is covered by a few inches of humus and fine surface soil.

Chemical Analyses

The following oxide analyses demonstrate clearly the abrupt losses in silica, calcium, magnesium, and sodium between Stages 2 and 3 and corresponding gains in alumina, iron, titanium and LOI. The increase in silica in Stage 4 is probably due to secondary resilication of the gibbsite apparently in the form of kaolin.

Stage 2 is absent in the weathering sequence of the spheroidal boulder. The fresh rock core of the boulder is in sharp contact with the strongly altered peripheral rock which falls in Stage 3.

OXIDE ANALYSIS

	SiO_2 (%)	Al_2O_3[1] (%)	Fe_2O_3 (%)	TiO_2 (%)	P_2O_5 (%)	CaO (%)	MgO (%)	Na_2O (%)	K_2O (%)	SiO_2 Residue (%)	LOI (%)	Total (%)
Stage 1	41.85	9.69	14.58	1.82	0.59	12.06	11.71	1.19	0.15	0.40	ND	94.04
Stage 2	42.03	10.55	14.36	1.99	0.51	11.69	10.01	0.79	0.09	0.41	1.27	93.70
Stage 3	0.75	43.22	23.55	3.79	0.34	ND	0.15	0.05	0.06	0.21	26.65	98.77
Stage 4	3.75	59.67	2.25	1.06	0.17	ND	0.04	ND	0.08	0.35	32.40	99.77
Core of spheroidal boulder	40.14	8.04	16.16	1.82	0.68	12.56	12.63	1.78	0.39	0.58	ND	94.78
Rim of spheroidal boulder to 12"	3.91	40.59	24.86	4.28	0.42	ND	0.34	0.05	0.06	0.17	24.06	98.74

[1] 1 Al_2O_3 by direct 8-hydroxyquinoline method.
[2] The remaining oxide analyses by tri-acid dissolution.
[3] ND—None detected.

CONCLUSION

Results from this study show that:

1. The primary mineral that is the principal source of the gibbsite in the area studied is plagioclase feldspar, Ab_{44} An_{56}.

2. The aluminum trihydrate occurs as pseudomorphs after plagioclase crystals, as finely divided grains in the altered rock groundmass, and as filling in stringers and cavities.

3. The plagioclase feldspar alters directly to gibbsite without passing through an intermediate kaolin stage.

4. The front of strong leaching is exceedingly sharply defined. Silica, lime, and magnesia are removed rapidly as the front advances. Alumina, iron oxides and some iron silicates persist. In the final stages alumina may migrate and be redeposited in fractures and cavities.

DEPT. GEOLOGY AND GEOPHYSICS,
UNIVERSITY OF HAWAII,
HONOLULU 14, HAWAII,
March 24, 1958

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Economic Geology
Vol. 53, 1958, pp. 854–866

GEOLOGIC CAUSES FOR FAILURE OF LONE PINE RESERVOIR, EAST CENTRAL ARIZONA[1]

GEORGE A. KIERSCH

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ABSTRACT

Failure of Lone Pine Reservoir to hold water admirably illustrates the result of complete disregard of geologic conditions. The earthfill dam, 101 feet high, built in 1934–36, proved satisfactory, but the reservoir developed serious leakage almost immediately and lost nearly half its stored capacity within one month. Silt-filled sinkholes, fissures, and openings were breached and an integrated ground-water system established by the pressure head of 74 feet of water in the lake. All attempts to "seal" the reservoir have failed.

Rocks of the area consist of: an undifferentiated series of Permian Coconino-Kaibab beds; thin Triassic sediments; both the volcanic (?) member (Lower basalt) and the upper member (Gravels) of the Pliocene Bidahochi formation, and locally capped by the Quaternary (Upper) basalt. The reservoir is largely in the Coconino-Kaibab sandstones and limestones; salt beds possibly occur beneath this series. The dam abutments are of well-jointed Lower basalt that overlies an irregular limestone unit. A regional, gently northwest dipping homocline is interrupted along

[1] *Acknowledgments:* The preparation of this paper has been substantially furthered by the cooperation and assistance of Dr. Parry Reiche, Fort Bragg, California. His first hand knowledge of the actual reservoir failure, initial geologic report, and subsequent stimulating comments and review of the manuscript have all contributed materially to the final text.

Appreciative thanks also to Donald B. Sayner, scientific illustrator, Tucson, Arizona, who prepared the drawings.

the west edge of the proposed reservoir basin by a subsidiary, north–south anticline.

This study considers, first, the cause of the reservoir failure and second, the feasibility of so sealing its basin as to render it usable. All rocks involved permit leakage; the jointed basalt with interbeds of ash; the inherently permeable Coconino–Kaibab beds; their secondary fractures and dissolved condition of sinkholes and interconnected openings; and the possible occurrence of salt beds at depth. The regional structure and a deep static water level provide a natural "piping circuit."

Reservoir sealing techniques, discussed in some detail, offer no sound economical solution for repair of Lone Pine Reservoir. Satisfactory undeveloped reservoir sites of similar capacity, available a few miles upstream, can be utilized for a cost similar to that of an attempted patching of Lone Pine Reservoir.

INTRODUCTION

FAILURE of Lone Pine Reservoir to hold water admirably illustrates the result of complete disregard of geologic conditions. The 101-foot earth and rockfill dam on Show Low Creek, a tributary of Silver Creek, and thereby of the Little Colorado River, is some 10 miles south of Snowflake and 7 miles northwest of Show Low, Arizona (Fig. 1). The dam was erected during 1934–36 as part of a Public Works Administration (PWA) program. No geologic advice was used in selecting the site or designing and constructing the dam (6).

HISTORY

Lone Pine Reservoir was dedicated on March 7, 1936.[2] Early Mormon settlers had picked the site 50 years earlier, but, lacking funds, no progress was made until the 1930's when the U. S. Government loaned the District $148,000. Planned benefits included irrigation of 5,000 acres of fertile land downstream in the vicinity of Snowflake.[3]

When dedicated, water in the reservoir stood 60 feet deep at the dam and extended some two miles upstream (Fig. 1). Noticeable leaks developed during the spring run-off in the following month. As a result, the Public Works Administration halted work on the then proposed appurtenant canal and irrigation system to await the outcome of further study and attempts to seal the leaks.

During the late spring of the same year leakage from the reservoir increased, and both the PWA and the State engineers became concerned for the first time with respect to the possible influence of geologic conditions. The first geologic study was requested in June, 1936, at which time Parry Reiche

[2] The historical account of the dedication, development of leakage, and subsequent attempts to seal-off the reservoir is largely from the files of the Snowflake Herald newspaper, 1936 and 1937.

[3] The dam was highest earthfill structure in Arizona at time of dedication. Howard S. Reid served as PWA engineer for the State of Arizona. Johannesen and Girand, engineering firm, Phoenix, Arizona, designed the structure, and Leo Frost was the contractor.

The 101-foot dam includes 11 feet of freeboard. Design capacity of reservoir at flow line level (90 feet) is 13,000 acre-feet. Highest water level attained while operated (April 7, 1936) was 74 feet (16 feet below spillway) or 7,580 acre-feet of storage. The runoff of Show Low Creek at the dam is up to 100 second-feet.

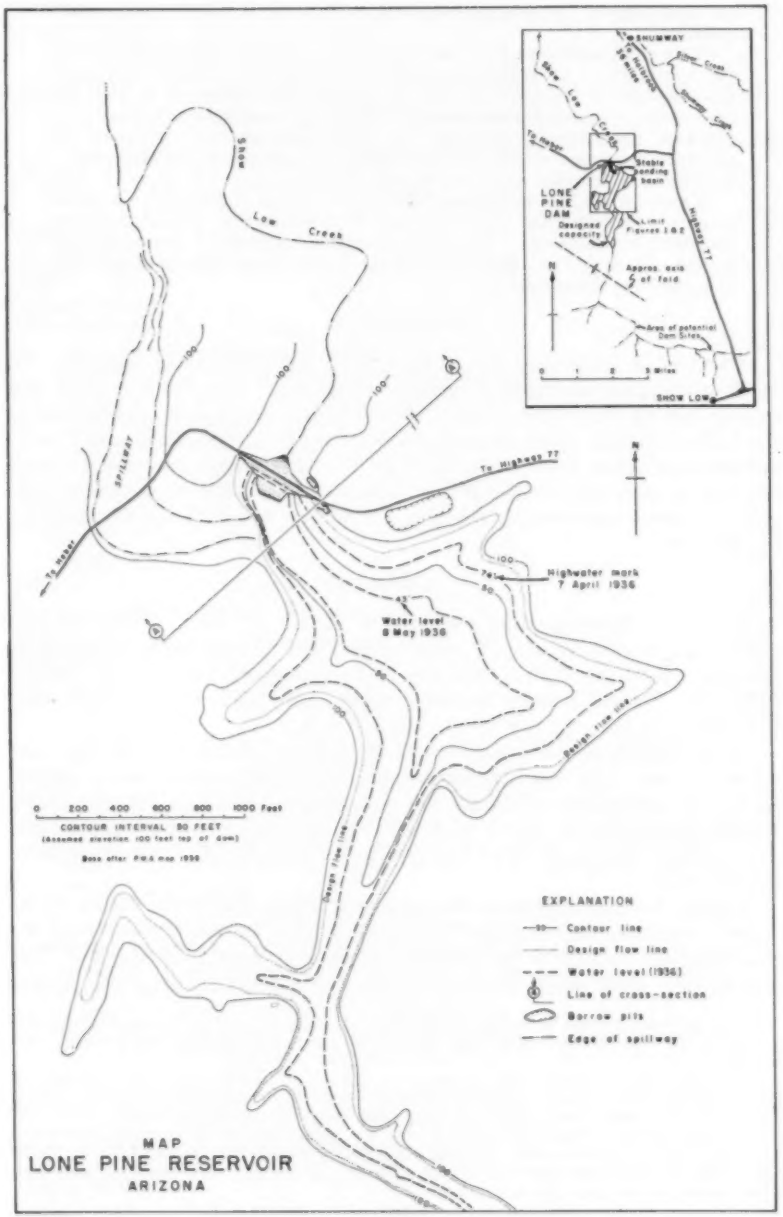

Figure 1

FIG. 1. Map Lone Pine Reservoir and vicinity, showing physical features and high-water level of reservoir in 1936.

(11) made a generalized geologic map of the reservoir, and submitted a report to the Soil Conservation Survey, Albuquerque, New Mexico. Essentially, his conclusion was: geologic conditions are so adverse that a remedy for the leakage is not economical. This recommendation was disregarded by the engineers-in-charge and by local irrigation officials. Restudy by PWA and state engineers convinced them otherwise, i.e., that plugging the sinkholes was not impractical, but would require time; that all leaks must be charted and the remedial procedure then applied. For the following several years numerous methods were used in an attempt to reduce the leakage. This work was largely ineffective. Efforts made during the winter and spring of 1936 are well indicated by excerpts from the Snowflake Herald newspaper.

On February 11, 1937, the water level in the reservoir stood at 46 feet, on February 26 at 48 feet with an inflow of 25 second-feet, while on February 28 water level was 47 feet with an inflow of 15 second-feet. A sinkhole running one second-foot was discovered on the 28th and sealed with clay; during the last few days of the month sinkholes leaking 2, 3, and 4 second-feet were discovered and treated. A three-man crew was on continuous duty patrolling and searching reservoir for new leaks.

The water level receded from the high mark of 74 feet of April 7, 1936, to the 43-foot mark on May 8, 1936 (Fig. 1); thus, approximately 5,700 acre-feet were lost in 31 days. This figure disregards inflow, head gate bypass, and evapotranspiration which should at least result in no net loss during the spring months.

During the late 1930's and mid-1940's, the U. S. Bureau of Reclamation studied the feasibility of its Snowflake project,[4] and F. A. Nickell (9) made a hasty geologic examination of the Lone Pine Reservoir. His conclusions were similar to those of Reiche (11). Later Glenn Lasson (7), also of the Bureau, reviewed the geologic conditions in greater detail and recommended that the reservoir site be abandoned as a possible storage basin. However, he found some justification for believing that the dam could serve to divert water eastward by tunnel to Shumway Creek (Fig. 3).

In 1953, the Arizona Game and Fish Commission became interested in the possibility of integrating the Lone Pine Reservoir into their statewide system of lakes and reservoirs. As part of this program, a geologic study of the Lone Pine Reservoir was made, and recommendations submitted by Kiersch (5). Again, as concluded by earlier investigators, use of the reservoir site for active storage did not appear feasible; instead, a new structure located nearby at a favorable upstream site was considered more promising and economical.

GEOLOGIC SETTING

The Show Low–Snowflake area is a few miles north of the Mogollon Rim, a prominent escarpment here marking the southern edge of the Colorado

[4] A proposed plan for further development of the water and land resources of the Snowflake area, Navajo County, Arizona. It includes a reservoir on Shumway Creek, a tunnel through which Show Low Creek would be diverted to the reservoir, rehabilitation of existing distribution system where necessary, and construction of new canals. The proposed multiple-purpose project would benefit flood control, recreation, and fish and wild-life conservation. The Snowflake project has not progressed beyond the planning stage at this date.

Plateau. The pre-Tertiary rocks dip one to three degrees northward from the Rim into the northwest-trending St. Johns syncline, north of Snowflake. All surface drainage is to the Little Colorado River. The thin Pliocene Bidahochi formation and an extensive overlying basalt blanket are nearly horizontal. Show Low Creek and its tributaries have dissected this flattish upland area, which extends northerly to near Shumway (Fig. 2). Youthful valleys carved by the ephemeral streams are steep-walled and a few hundred feet deep. Silver Creek to the northeast, which is largely fed by a series of springs, is the principal perennial stream in the region.

ROCKS OF THE AREA

Most of the reservoir basin is underlain by Permian sandstones, sandy limestones, and limestones (outcrops) lithologically resembling the Coconino and Kaibab formations (Fig. 2). Locally overlying these are Triassic sediments, followed by the more widespread Pliocene Bidahochi formation consisting of a Lower basalt and thick fluviatile gravel, sand and tuffaceous beds. Capping the section is an extensive Quaternary (Upper) basalt. Recent alluvium blankets the stream valleys.

Because the composition, and lithologic aspects of the Coconino and Supai formation at depth beneath the reservoir are of importance, they are discussed below.

Coconino and Supai Rocks at Depth.—Thickness of the Coconino rocks in the Lone Pine area is unknown; however, the Coconino probably approaches 200 feet, based on scattered areal information. Regionally, the Coconino thins southward from a thickness of over 800 feet in the Holbrook area (3, p. 41) to a thin and irregular section near the Mogollon Rim. Within the belt of rapid thinning (includes Lone Pine site), the Coconino may intertongue with the underlying Supai beds, in a manner similar to the conditions recognized throughout the southern Defiance Plateau area. Here the Supai interfingers and grades laterally into the lower and central part of the Coconino (DeChelly) sandstone (10).

At Navajo (45 miles northeast of Holbrook), a deep test well penetrated 800 feet of almost solid salt in the Supai formation (13). A deep wildcat well 9 miles northwest of Snowflake (16 miles north of Lone Pine) encountered a thick section of alternating salt, other evaporites, and sandstone in the Supai formation beneath the Coconino (14).

If Supai beds intertongue with the thinning Coconino along its southern margin, as at the Defiance Uplift, any salt beds are probably higher stratigraphically than such beds well within the Supai "basin" of deposition.

Permian Series, Undifferentiated.—The Coconino and Kaibab formations as locally developed, comprise sandstones and sandy limestones, with minor amounts of limestone (Fig. 2). Rapid local changes in lithology both vertical and lateral, precluded separate mapping of units correlative with the Coconino and Kaibab formations. Only near the sinkholes along the western edge of the reservoir (Fig. 2) is the upper part of the series predominantly Kaibab-like limestone; here approximately 50 feet of limestone crops out. Elsewhere

in the area (Fig. 2), limestone is absent or is limited to one or more thin beds near the top of the Permian series.

The district is near the southeastern margin of the Kaibab basin of deposition (8), hence rapid changes in lithology and unusually high detrital content are to be expected.

MEASURED SECTION NO. 1 NEAR SOUTH LIMIT OF AREA REPRESENTED BY FIGURE 2

	Thickness in feet
Upper Bidahochi (erosion surface)	
Gravels: Coarse-to-fine rock fragments	
Coconino–Kaibab (undiff.)	
Sandstone: whitish to blue-gray, cross-stratified on small scale, typical Coconino aspect	19
Sandstone: limy, whitish, massive, horizontally bedded, locally weathers reddish (resembles basal unit)	33
Limestone: sandy, blue-gray, thin-to-thick bedded	15
Sandstone: limy, whitish, massive, horizontally bedded (base of exposure at stream bed elevation)	42
Total	109

MEASURED SECTION NO. 2 NEAR DOWNSTREAM END OF SPILLWAY

	Thickness in feet
Coconino–Kaibab (undiff.)	
Limestone: blue-gray, (resembles Kaibab)	4
Sandstone: limy, whitish, cross-stratified small-medium scale, (resembles Coconino) (base at spillway level)	69
Total	73

The upper contact or surface of this series invariably exhibits solution, with undulating surfaces, channeling several feet deep, and a highly argillaceous weathered mantle.

Post-Permian formations are chiefly above the design flow line, forming a thin mantle over older rock along the sides of the reservoir basin and the upper parts of the abutments of the dam. They are not directly relevant to the reservoir failure. However, had the Coconino–Kaibab beds "held water," these younger rocks would have allowed significant leakage. In addition, one unit, the upper Bidahochi member, was utilized for fill.

Triassic Sediments.—In the spillway cut, northwest of the dam, the Coconino–Kaibab beds are immediately overlain by approximately eight feet of dense claystone. This material is probably correlative with the Moenkopi formation that crops out northeast of the site along Shumway Creek (Fig. 3), but possibly represents Chinle that occurs a few miles to the north near Shumway.

Bidahochi Formation.—A basalt flow and volcanic debris, and a series of gravel, tuffaceous sediments, and sand assignable to the volcanic (?) and upper members of the Bidahochi formation locally overlie the Triassic beds and underlie Quaternary lava. Lower member Bidahochi beds do not occur near the dam site; closest locality is north of Navajo, Arizona (12).

In the spillway (Fig. 2) the volcanic (?) member comprises a six-foot bed of coarse sand with minor interstitial silt, overlain by four to six feet of tuffaceous sand and capped by the Lower basalt flow. The upper surface of the tuffaceous sand is channeled and weathered. The basalt, dense and fresh above, has a basal altered zone.

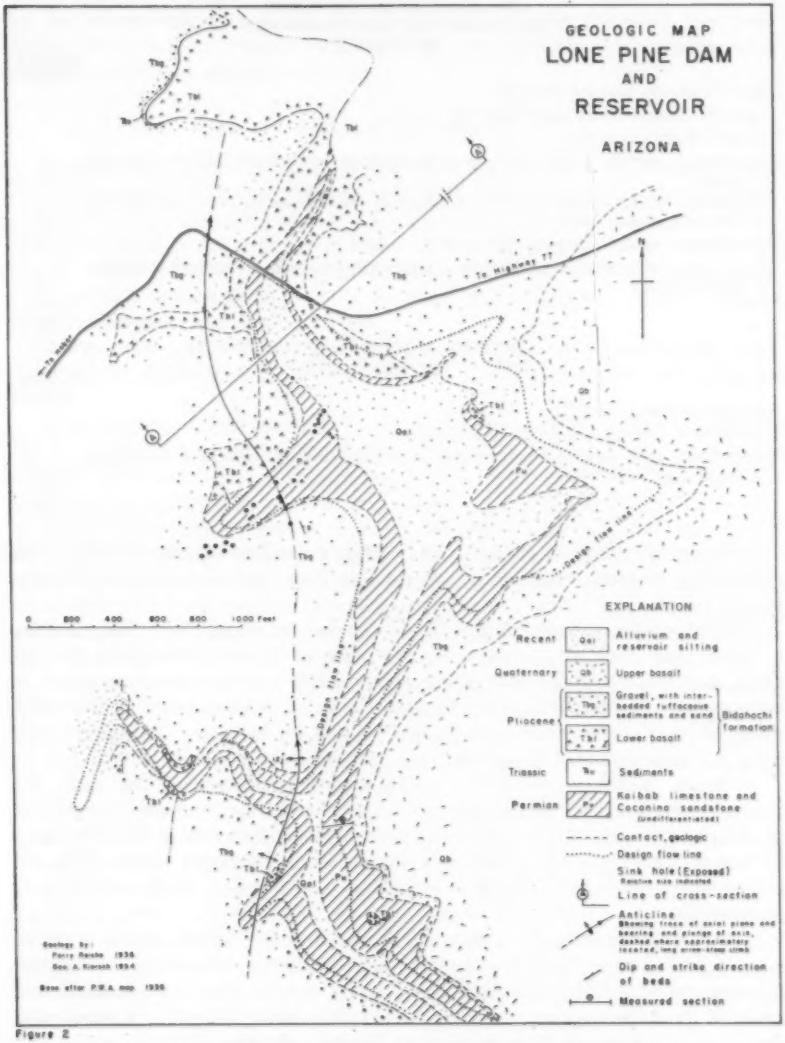

FIG. 2. Geologic map, Lone Pine Reservoir and vicinity.

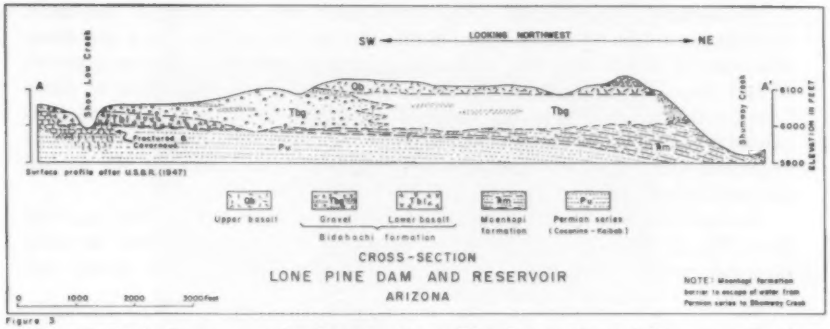

Figure 3

FIG. 3. Geologic cross-section between Lone Pine Reservoir and Shumway Creek.

The Lower basalt, which forms the upper two-thirds of the dam abutments, is a normal-appearing, columnar-jointed, olivine-bearing rock. Its upper surface shows minor channeling and a weathered zone one to three feet thick, in which residual clay retains initial structures and textures. The Lower basalt is a tongue locally; where it filled channels in the underlying rocks, the flow may total nearly 50 feet thick (Fig. 3). Elsewhere, for example, west of Show Low Creek, only its upper 5 to 20 feet is present. This western thinning in part results from overlap on the truncated pre-Cretaceous rocks. The Lower basalt pinches out near the western edge of the reservoir (Fig. 2) along the flank of an asymmetrical fold which restricted its advance in that direction.

The upper member of the Bidahochi comprises a thick section of moderately cemented gravel, and tuffaceous sediments and sand (Fig. 2). These beds are undoubtedly an extension of those mapped by Darton (1) near the Mogollon Rim to the south, and correlate with upper Bidahochi outcrops to the northward (12). The upper member, as exposed in a 25-foot section by the main borrow pit, east of Show Low Creek (Fig. 1), consists of crudely-bedded, weak to moderately cemented, coarse to fine gravels. The subrounded to rounded rock fragments include Coconino-type sandstone, Kaibab limestone, chert, quartz, fresh and weathered basalt pebbles and cobbles, quartzite, and petrified wood; sporadic soft pebbles are of clay and sandstone. Pebbles and cobbles (one-half to six inches) comprise approximately 65 percent; the remainder is of coarse sand and small sandstone pebbles (under one-half inch). The reddish matrix is quartz sand with minor fine silt.

The upper Bidahochi sediments range in thickness up to 120 feet according to the local relief upon which they were laid down (Fig. 3). All are fluviatile and show rapid laterial and vertical gradations.[5]

[5] The bedding is indistinct, with stout lenses and channels. At the borrow pit there are several lenses of light-brown sand; one lense over 100 feet long and three to five feet thick, pinches out abruptly from its average cross section.

At Shumway Creek, the western marginal section is largely tuffaceous sand with interbeds of thin shale and a basal gravel (Fig. 3) whereas 1200 feet across the valley the eastern section includes no basal gravels. Instead the Moenkopi formation is overlain by sands and silts (22 feet thick) capped by 11 feet of fresh-water limestone.

Quaternary Upper Basalt.—An Upper basalt flow, averaging 20 feet thick, blankets the relatively smooth post-Bidahochi surface widely. In a few channels, one of which near the southern limit of Figure 2 was approximately 40 feet deep, the basalt thickness is correspondingly greater. West of Show Low Creek Valley, erosion has stripped any Upper basalt unit that may have existed (Fig. 2) except at the south end of the reservoir. The flow probably originated some miles to the southeast. Like the Lower basalt, it is a normal olivine-bearing aphanite.

Recent Alluvium.—Alluvium and backfill silt blankets much of the reservoir floor (Fig. 2 and 4a); dark-brown silt is at least 20 feet deep behind the dam. Both the reservoir silt and valley alluvium have a high moisture content and function as a water-holding blanket.

STRUCTURE

None of the moderate-scale folds, monoclines, and domal uplifts that interrupt the regional homocline structure influence conditions at Lone Pine directly. The nearest are an open fold south of the reservoir (Fig. 1 inset), and a domal uplift just north of Shumway near Taylor.

However, Show Low Creek canyon at the reservoir site parallels and is incised in the gentle, east limb of a small asymmetrical northward plunging anticline (Fig. 2). Locally, as in the upper part of the reservoir, the westward dip approaches 10 degrees; near the dam site and area of abundant sinkholes, the eastern limb dips up to three degrees northeastward, as does the Coconino–Kaibab series elsewhere in and near the reservoir. The northward plunge of the local fold combined with the regional attitude projects the Coconino–Kaibab series beneath stream level, approximately 800 feet downstream from the dam. The channel is carved wholly in the Lower basalt for several hundred feet before the northward plunge reverses downstream; near this point a small fold and associated faulting again elevates the Coconino–Kaibab rocks from a 20-foot channel section to 75 feet above stream level and for a second time the channel continues for several miles in these rocks.

A strongly developed joint system in the Coconino–Kaibab series includes sets that strike N. 70–90° W. and N. 15° E.; both dip essentially vertical. Throughout the Coconino–Kaibab series and particularly where limestone crops out, the joints and bedding planes are widened by solution. Locally, where the limestone is relatively thick, as it is immediately upstream from the dam (Figs. 2, 3), wide openings, numerous sinkholes, and an interconnected system of caverns have developed.

Sinkholes.—The minor folding and faulting fractured all rocks involved and facilitated solution in limestone and limy sandstone beds by percolating water. Subsequently, sinkholes developed closely associated with the flexures (stages illustrated elsewhere, 4., p. 800). Sinkholes near the fold axis west of the reservoir in areas thinly blanketed by gravel were reopened when water pressure of the nearly full reservoir breached the gravel cover (Fig. 2 and 4b). Reiche (11) noted many of the sinkholes in the basin as ranging from 2 feet to 30 feet in diameter (Fig. 2).

FIG. 4a. Looking upstream into reservoir site from just upstream, west abutment Lone Pine Dam. Lower basalt in foreground, Coconino–Kaibab rocks concealed by silt blanket in channel and below berm central foreground. Upper basalt forms skyline.

FIG. 4b. Moderate-sized sinkhole in limestone located in side canyon upstream from dam. Although partly filled with silt, sinkhole illustrates typical "breached" and reopened structure.

At "The Sinks," 16 miles to the northwest, the large sinkholes are concentrated near the axial traces of an asymmetrical anticline and syncline (1 p. 202). The Kaibab limestone cap, 20–30 feet thick, is underlain by a thick section of Coconino sandstone that is partly exposed in the sink structures. Individual cracks and fissures associated with the fold extend to depths of at least 100 feet (some reported deeper), and range from a few feet to at least two miles in length and from less than an inch to 10 feet wide at the surface (3., p. 56).

It seems quite possible that a thick section of salt beds in the Supai, like those described above as having been noted in the formation near Snowflake and Navajo, occur at "The Sinks" and is largely responsible for the extensive sinkholes, deep fissures, and interconnected openings. Harrell and Eckel (3, p. 57) suggest an origin due to unequal settling over salt beds. Site conditions at Lone Pine are similar in many respects to those at "The Sinks."

SUMMARY OF RELEVANT GEOLOGIC CIRCUMSTANCES

Solution began to develop permeability in the Coconino–Kaibab beds soon after the withdrawal of the Kaibab marine embayment. Since marked regional elevation is not indicated for that time, it is doubtful that this initial "opening up" was deeply effective. A second interval of erosion in pre-Bidahochi time resulted in local stripping of the Triassic sediments and further channeling of the Coconino–Kaibab rocks. It is highly probable that pre-Bidahochi folding and warping closely fractured the heavy Coconino sandstones, integrating and extending the subsurface circulation, i.e., the minor anticline along the west side of the proposed reservoir basin.

The upper Tertiary uplifts facilitated deep and active circulation of fresh groundwaters, and the extensive joint systems of the Kaibab–Coconino must have been well-widened concurrently with cavernous solution of limestone and any possible salt bodies at greater depth. The Bidahochi rocks and Quaternary basalt pre-date the present drainage pattern, probably incised by regional uplift, although climatic changes may have been a factor. The rapid influent seepage of surface waters was facilitated by the regional downstream dip and fractured condition of the pre-Tertiary beds, the depth to the static water level, and by the cutting of bedrock channels by Show Low and neighboring creeks, backfilled and re-cut, eventually, through well-jointed lavas and coarse, loose clastics.

The actual failure of the reservoir is explicable in terms of the permeabilities developed and the gentle northward dip of the pre-Tertiary beds, as just noted, although the sandstone has an appreciable inherent porosity. Had the Permian reservoir rocks been more adequately impervious, serious leakage would still have been facilitated by the open joints of the Lower basalt (and underlying ash bed) which forms the dam abutments, and the generally open texture of the Bidahochi sands and gravels above. As it was, the reservoir did not remain full enough for sufficient time to develop these additional weaknesses.

METHODS OF SEALING RESERVOIR LEAKAGE

Reservoir-sealing techniques in common use offer no sound economical solution for the repair of Lone Pine Reservoir.[6] The hydrostatic pressure exerted by a full reservoir (90 feet) would rupture and flush the sealing material in a patched opening, unless bonded very strongly. Thus, although

[6] (1) Grout the reservoir rock using an adequately spaced grid pattern of drill holes. A neat-cement grout is too thin to fill and seal the existing openings. A clay-cement grout slurry would likely be ineffectual, except in the fissures and smaller openings. Emplacement of hot asphalt in the cavities would seal-off the leakage for a limited time. Long-term use of asphalt invariably results in reopening the cavities due to: (a) gradual deformation and flow of the asphalt under the reservoir pressure or slumping under its own weight in a partially filled opening; and (b) solution of the limestone after asphalt is injected (2, p. 1002). Both of these causes for leakage can be prevented if the asphalt filling is backed up by a cement grout. Although the asphalt-cement grout would consolidate the reservoir rock and create a water-holding basin, it would be an extremely expensive method for repairing Lone Pine Reservoir.

(2) The individual sinkholes could be located, cleaned out in depth and backfilled with concrete. This would remedy the large openings but not the abundant smaller solution-widened

some patching is practical, it is likely that further operation of the reservoir would reopen some "avenues-for-escape." Undoubtedly some of the silt presently sealing the stable ponding basin (Figs. 1 and 2) would be flushed by the hydrostatic head of a near-capacity reservoir.

As all the reservoir rocks are permeable, there is no possibility of diking off parts of the impoundment area to materially reduce leakage.

Any effective repair method would be very expensive and there is no assurance short of actually paving the reservoir basin, that it will be completely satisfactory and effective; the interconnected system of openings appears to extend to depth within the Coconino rocks.

CONCLUSIONS

An efficient repair job to eliminate the leakage from Lone Pine Reservoir is uneconomical. True, engineering-wise, almost anything can be accomplished if cost is not a factor. However, moderate cost repair methods and techniques applicable to the leakage problems presented here give little promise of lasting effectiveness.

Satisfactory undeveloped reservoir sites in sound rock occur upstream from Lone Pine in the stretch three to four miles downstream from Show Low (inset, Fig. 1). A sizeable share of the Lone Pine Reservoir's design capacity can be impounded at any of these sites at a cost comparable to that of an attempted patching of Lone Pine Reservoir. Had a geological study been undertaken as part of the site selection and planning phases of the Lone Pine Dam, this conclusion would have been apparent; and the total loss of funds spent for construction and maintenance attempts, not to mention the personal losses incurred by local inhabitants, could have been avoided.

SOUTHERN PACIFIC CO.,
SAN FRANCISCO, and
1010 GROSVENOR PLACE,
OAKLAND, CALIFORNIA,
Mar. 25, 1958

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joints, fissures, and "escape openings"; consequently method only partially effective, yet is very expensive.

This approach was attempted in 1936–37 using clay material. It proved unsuccessful because the reservoir pressure invariably "breached" the weakly-bonded backfill.

(3) Another possible backfilling technique would be to wash coarse sand and gravel into the cavity first and follow this gravel packing by solidifiying with a heavy grout slurry that bonds strongly. Like method no. 2, a very expensive, two-stage operation.

4) Clean off the reservoir surface, backfill the major openings with concrete, asphalt, gravel packing, or clay, and "pave" the reservoir basin with an appropriate asphaltic material. Of course, this is not practical for the upper third of the reservoir basin located in the blocky and nearly vertical-walled sector. Although effective against major leakage, method very expensive.

(5) Clean off the reservoir surface and backfill the openings (no. 4 above); then blanket the surface with several inches of swelling bentonite. To hold the bentonite in place, conceal with a 6 inch layer of soil. Like method no. 4, this technique is expensive and not practical for steep-walled sector.

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Economic Geology
Vol. 53, 1958, pp. 867–876

THE LEAD–ARSENIC–SULFIDE ORE DEPOSIT OF BACU LOCCI (SARDINIA—ITALY)

STEFANO C. ZUCCHETTI

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ABSTRACT

The lead-arsenic-sulfide ore deposit of Bacu Locci lies in southeastern Sardinia (Italy) and more precisely in Cagliari province.

The mineralization occurs in Paleozoic rocks, both sedimentary (Lower and Middle Gothlandian shales) and igneous sericite gneisses and lamprophyres); overlain by discordant Eocene formation.

The shales are cut by many large, parallel, inclined faults, and also by bedding faults. The faults upon entering the igneous rocks form a stockwork.

It is considered that the fracturing was a late feature of the Hercynian orogenesis, after the last Paleozoic igneous intrusions.

The fractures were occupied by medium-temperature hydrothermal solutions and filled with metallic ores and their matrixes.

The mineralized bodies occur in highly-inclined lodes, within the Silurian shales, in stratiform lodes concordant with the shales, and also in a stockwork within the igneous rocks.

The only economic minerals are galena and arsenopyrite, in about the same rate proportions. Other sulfides, such as sphalerite, pyrite, chalcopyrite, and pyrrhotite, occur in very small quantities.

Therefore the deposits, because of this singular and unusual association, is distinct among meso-hydrothermal deposits.

Among the gangue minerals quartz is common, calcite and siderite are subordinate, and fluorite is rare.

The author has studied some dozens of polished and thin sections of the primary minerals obtained from many samples collected personally. The mine has also a "secondary" deposit characterized by three typical zones: a) the upper, or outcrop zone of ferro-oxidized minerals; b) the middle, or oxidation zone, with lead-arsenic oxidized minerals; and c) the lower, or cementation zone, with supergene minerals.

INTRODUCTION

THIS paper deals with the lead-arsenic sulfide ore deposit of Bacu Locci, which has not previously been described in the literature. Its economic minerals are galena and arsenopyrite, in about equal proportions; other sulfide minerals are minor sphalerite, pyrite, chalcopyrite, and pyrrhotite.

The chief interest of the deposit is not so much the paragenesis of galena and arsenopyrite, but the unusual ponderal preponderance of these minerals. Deposits of sulfide ores of copper, lead, zinc, and iron carrying associated arsenopyrite as an accessory mineral are well known all over the world (2, 4, 8, 10, 11, 12, 13, 16, 17); but such an abundance of arsenopyrite with galena is unknown in other deposits. Therefore the Bacu Locci deposit is unusually distinctive among the large group of meso-hydrothermal deposits.

GEOLOGICAL FEATURES OF THE ZONE (5)

The mineralization occurs essentially in Paleozoic rocks, both sedimentary and igneous, overlain, discordantly by Eocene formations. There is a long stratigraphic break between the upper Paleozoic and the Tertiary rocks; the Carboniferous, Permian and Mesozoic sediments are missing.

Paleozoic Sediments.—These consist of lower and middle Gothlandian sediments, whose maximum thickness is several hundred meters, mainly represented by black phyllitic shales commonly graphitic, with graptolites, by gray shales, and in places by real phyllites and schistose sandstones.

In addition, there is a series of intermediate lithological varieties, with schistose texture, some with limited crystallinity (clayey or micaceous sandstones, sandy shales) and others crystalline (quartzose shales, phyllitic shales, quartzose phyllites). The limey beds with *Orthoceras*, and the lime schist formations, typical of the upper Gothlandian period, are missing. The Silurian sediments generally dip W and SW at an average angle of 15° to 40°.

Paleozoic Igneous Rocks.—The Paleozoic igneous rocks consist of the products of the first and the fourth magmatic cycle, active in southeastern Sardinia during the Paleozoic (sericite gneisses cycle and "lamprophyres and dioritic porphyrites" cycle respectively, 3, 4). Granites, porphyritic granites, and also porphyries, typical of the second and the third magmatic cycle, are lacking in this area.

Sericite gneisses.—This is a rock series, notably schistose, in places with a porphyritic texture, and with varying grain sizes, from very small up to gigantic crystals. There are various petrographic types; although they have similar chemical composition, they differ in mineralogic composition and in structural characters. Thus, there are gneisses, (including "occhiadini" types), with very little sericite, and gneisses, in which the feldspars are nearly

totally sericitized and the quartz is more or less intensely crushed. In addition there are sericite schists, sericitic phyllites, and tufaceous facies. Some varieties are formed partly of sedimentary materials and partly by eruptive tufaceous ores (metaschistous rocks).

All of these rocks represent the product of submarine volcanic activity, which was contemporaneous with the more recent Silurian sediments (Gothlandian ones). Submarine magmas and tuffs erupted through fissures in the sediments and spread over extended surfaces.

The rocks so formed, covered by successive intercalated sediments, underwent the same complex tectonic and metamorphic history. They now occur in more or less thick and extensive sections, and only subordinately in dikes.

Lamprophyres.—These are basic rocks, with an aphanitic texture but in phases exhibiting flow structure. Some are porphyritic with a microcrystalline groundmass. Mineralogically they consist of plagioclase with one or more of amphibole pyroxene or olivine. There are thus different facies such as amphibolitic and pyroxenic spessartites, pyroxenic olivine-odinites, and amphibolitic micaceous malchites.

These rocks are the product of the fourth and last Paleozoic magmatic cycles in the island. They are later than both the Silurian sediments and the sericite gneisses of the first cycle, the granites of the second, and the porphyries of the third cycle, and preceded both the post-Paleozoic sediments and the pneumatolitic and hydrothermal manifestations which, as a concluding phase of the Paleozoic Hercynian volcanism, gave rise to the ore mineralization.

The occurrence of the spessartites is generally in lodes whose thickness varies from few centimeters to some meters and also in dikes several tens of meters in thickness. In the Silurian shales and in the sericite gneisses they may lie remote from the Hercynian intrusive bodies, as the mine area. Here is a large spessartitic lode that has been followed from the surface to a maximum depth of over 100 meters in the Su Spinosu section. This rock, with a doleritic texture, consists essentially of basic plagioclase (labradorite-bytownite) both idiomorphic and elongated, and amphibole (hornblende), which is locally altered. It also contains rare quartz crystals with an irregular outline.

Eocene Formations.—The Eocene formations rest discordantly on the Silurian rocks (Mount Cardiga transgression). Near the mine they are about 100 m thick and consist, at the base, of a conglomerate whose pebbles are schist, gneiss, quartz, and calcareous detrital constituents, several centimeters across. These are cemented by a thin siliceous and clayey detritus, that is a product of the degradation of the Silurian formations.

In places the basal conglomerate is replaced by a clayey-marly formation, gray to violet-blue in color, that may also be a product of the alteration in situ of the same Silurian rocks. In other places, the basal formation consists of a well cemented sandstone (west of Mount Cardiga).

Over the basal complex there are sandstones composed of quartzose or arkosic detritus, cemented by clayey or ferruginous material, or by calcareous and siliceous substances. The nummulitic limestones follow. The Eocene formations dip gently westward.

FRACTURES

The Paleozoic formations are cut by a system of fractures that were opened during phases of tectonic settlement that followed the last Paleozoic magmatic intrusions. These formed channelways for hydrothermal mineralizing solutions. The fracture system extends along both sides of the Bacu Locci valley, from the mill upstream for over 2 km, and with a maximum width of over 200 m.

The mineralized fractures are numerous and give rise to stoping areas. They have an average strike about N 30° W and dip from 60° to 80° WSW and thus cut across the stratification of the beds. They vary considerably in length, width and depth; for instance, the fracture of the Su Spinosu section, which was followed down dip for about 100 m, has a maximum length of more than 300 m and a maximum width of 8 to 9 m; the fracture of the Bruncu Spinosi section, has a maximum thickness of 5 m, a length of about 80 m at the upper level (287 m) and over 100 m at the lower level (270 m) and has been explored for about 40 m below the surface.

In addition to these principal fractures, there are other fractures that link them together, locally called "crossing lodes" ("filoni incrociatori"). These splits occur both within Silurian shales and at the contact between them and sericite gneisses; commonly mineralized splits have graphitic shales on the footwall and gneiss on the hangingwall (Fig. 1).

It must also be noted that the mineralization is not only confined within the steeply dipping fractures, but in many places it extends outward from the fractures along the bedding of the Silurian shales, in stratiform shape.

The steeply-dipping fractures behave differently in the shales and gneisses. The gneisses, being hard and coherent rocks, broke and cracked minutely into many small fractures and crevices, and in places became mylonized. The main splits, therefore, on entering the gneisses, tend to form stockworks.

Similar features resulted where fissures entered the great spessartite lode of the Su Spinosu section.

Different behavior resulted where the fissures entered shales, which being less compact, softer, and more schistose and plastic than gneiss, caused swellings and splits of large size.

In summary, the following regarding the Bacu Locci occurrence may be noted:

1. The Silurian shaly formations contain numerous, large discordant fractures;

2. The principal fractures have generally similar shape, strike, and dip;

3. The fractures are mineralized and commonly include pre-ore breccias ("interramento");

4. Into the Silurian formations there was intruded a large lamprophyric lode (spessartite), resulting from the magmatic activity that concluded the Hercynian volcanism;

5. The spessartitic lode is in places mineralized along thin reticulating fractures.

These observations are in close agreement with those of Cavinato and

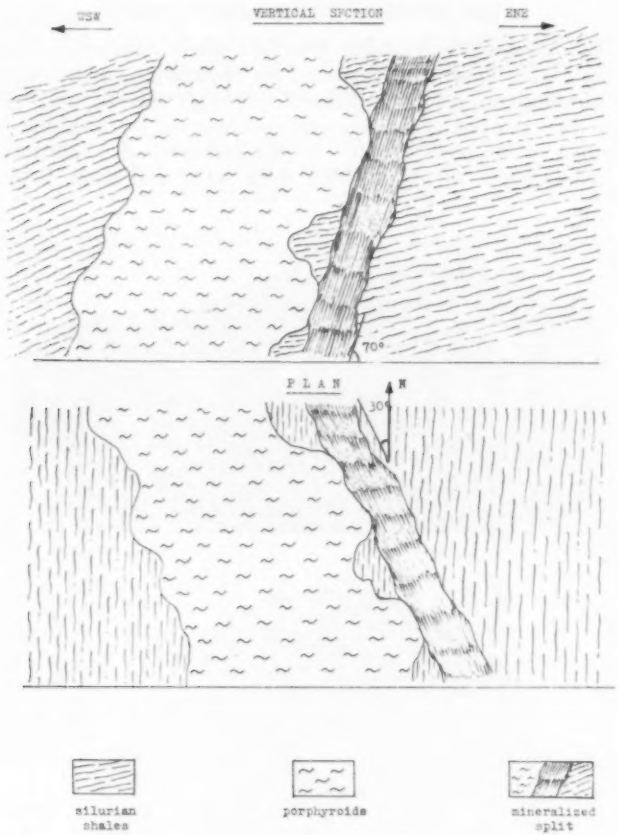

FIG. 1. Plan and section of a split at the contact between shale and gneiss (porphyroids refer to gneiss).

Zuffardi (6) in their paper "Geologia della miniera di Montevecchio (Sardegna)" who concluded that the fissuring at Montevecchio was later than the Hercynian orogeny and resulted from settlement following lamprophyre intrusions.

This conclusion could also apply to the Bacu Locci deposit by slow and continuous consolidation of the deep magmas that gave rise to the lamprophyres. These magmas, cooling and shrinking during their solidification, could have caused contraction in the overlying sedimentary and igneous rocks.

This hypothesis is perhaps the most likely and the most valid to explain the genesis not only of the principal fractures, but also of the "crossing lodes" and the other splits.

THE MINERAL DEPOSIT AND ITS ORIGIN

Mineralization.—The fractures described above constituted channelways for solutions from which were deposited the ore and gangue minerals.

The metallization, a low-temperature (9) hydrothermal one, was clearly later than the formation of the fractures and breccias, the fragments of which are cemented by the ore minerals. At the 24.5-level of the Bruncu Spinosi section, for example, the split within shale walls, and about 3 m thick, is

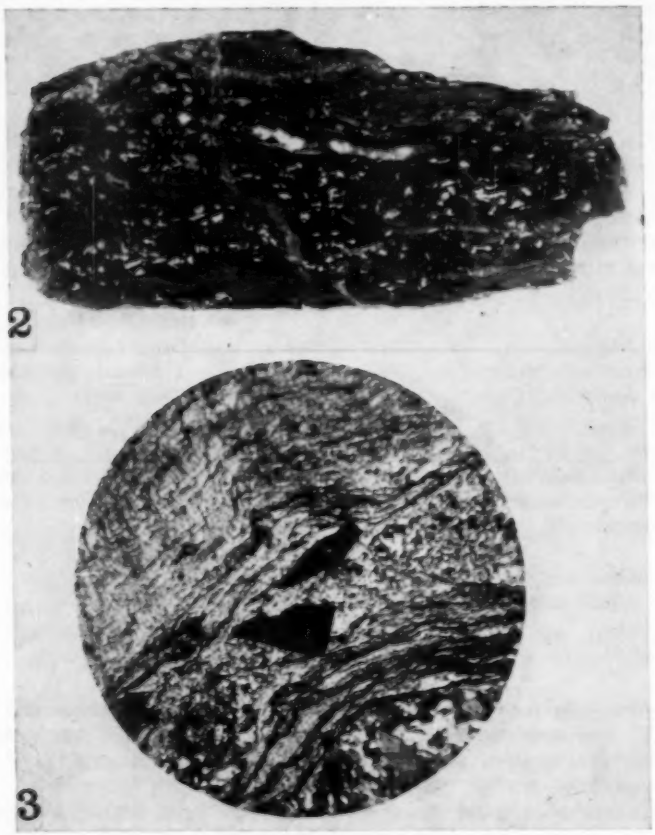

FIG. 2. Mineralization consisting of arsenopyrite with subordinate pyrite, and quartz veinlets, within Silurian shales. Brecciated mineralization at —24.50 sublevel of the Bruncu Spinosi section. Natural scale.

FIG. 3. Photomicrograph of thin section. Mineralized Silurian shale (same as Fig. 2). In the middle two crystals of arsenopyrite; on the lower right, a little knot of hydrothermal quartz. X-nicols, × 25.

nearly completely filled by altered shaly material, cemented by ore—mostly arsenopyrite with subordinate galena and pyrite—and by quartz matrix. In addition, the mineralization penetrated the brecciated fragments, giving rise to disseminated crystals of arsenopyrite with a little pyrite, a few millimeters in size (Figs. 2, 3).

The mineralization in the fractures may reach a continuous length of several hundreds meters along the strike and for several tens meters down the dip; in the Su Spinosu section a fissure was stoped continuously for 300 m along the strike, and for 100 m down the dip, but the width decreased from a maximum of 8 to 9 m to a minimum of some centimeters. All of the mineralization is not ore. In the splits the minable ore is concentrated in ore shoots..

The lodes are crustified with layers of gangue alternating with crusts of sulfides.

In many cases the crustification is symmetrical on both walls. The walls have been narrowly altered by sericitization, argillization, and silification. As already mentioned, the mineralization also extends outward not from the fissures into shale walls but less into gneiss lamprophyre. However, where stockwork fractures have been formed in gneiss and lamprophyre, small ore bodies are formed in the walls.

Where the walls are Silurian shale bedded deposits may extend out from the fissures, along the dip of the shale (15–20°), for some tens of meters, and for over 100 m along the strike, the thickness being 5–6 m. These bedded bodies are quite distinct from the fissure veins and are the only ones known in all of Sardinia. They now yield the greater part of the output of the mine.

At the Su Spinosu section (St. Riccardo's level and sublevels) the great mineralized split is in many places at the contact between the shales and the great spessartitic dike, which is up to 9–10 m thick. On some levels, the split followed both sides of the dike, as is shown in Figure 4.

From the mining point of view, the deposit is divided into two quite different parts: the "primary" deposit of sulfide ore, which is the most important concentration in the mine, and the "secondary" deposit.

MINERALOGY OF THE PRIMARY ORE

From samples collected underground I obtained several dozen polished and thin sections, which were studied in the laboratory under the microscope (14, 15).

The Bacu Locci ores consist of the following:

Metallic minerals: arsenopyrite and galena (dominant), and subordinate ferriferous sphalerite (marmatite), pyrite, chalcopyrite, and pyrrhotite.

Gangue minerals: quartz (dominant); calcite and siderite (very subordinate); and fluorite (rare).

The most abundant mineral in the deposit is arsenopyrite. It occurs mostly as fine-grained aggregates, commonly intimately associated with the other sulfide minerals, particularly with galena. In places it occurs in crystals of elongated prismatic habit and lamellar shape, as for instance in the

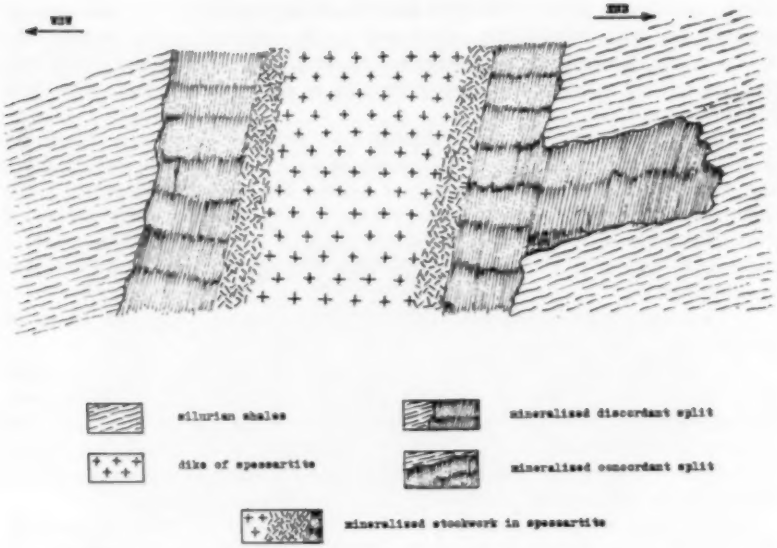

FIG. 4. Cross-section at the — 40-meter sublevel, St. Riccardo's level, Su Spinosu Section.

breccia ore of the lower levels of the Bruncu Spinosi section (Figs. 2, 3). Under the microscope it shows a white metallic color, with very high reflecting power, and pronounced anisotropism under crossed nicols. It includes other sulfides, notably galena and pyrite.

Galena generally accompanies arsenopyrite. Mostly it is well crystallized; some of it is microcrystalline.

Some galena contains fine arsenopyritic inclusions.

Sphalerite, pyrite, chalcopyrite and pyrrhotite are quite subordinate. The sphalerite, mostly ferriferous (marmatite), is always associated with galena in massive fine-grained aggregates. Pyrite always accompanies arsenopyrite in the shape of mircocrystalline aggregates and also of isolated crystals mostly with a hexahedral habit. Some of it is in the core of arsenopyritic grains and was deposited before arsenopyrite. Chalcopyrite and pyrrhotite occur with each other and with galena. Both contain small inclusions of quartz and galena.

The polished sections also revealed the presence of bornite, tetrahedrite, bournonite, argentite, and stephanite.

Gold is also present, interlocked with silver-bearing sulfide minerals. Assays of the mill concentrates made by the mine laboratory show a content of silver from 1,000 to 1,200 gr per ton of run of the mine and gold content from 5 to 10 gr per ton.

The chief gangue is quartz, in aggregates with a microgranular or crypto-

crystalline structure, or in isolated crystals. Silification of the wall rocks also occurs. Calcite and siderite are less abundant and fluorite is very rare.

THE SECONDARY DEPOSIT

The secondary deposit of the Bacu Locci mine is mostly in the upper part of the Su Spilloncargiu section. Although it is much smaller than the primary deposit, it is interesting on account of its genesis and mineral content.

From the surface down to the bottom there are three distinct zones: a) the upper, or outcrop zone; b) the middle, or oxidation zone; c) the lower, or cementation (enrichment) zone (1, 4, 11).

Outcrop Zone.—With the underlying oxidation zone, the outcrop zone represents the part of the primary deposit that has undergone oxidation. The

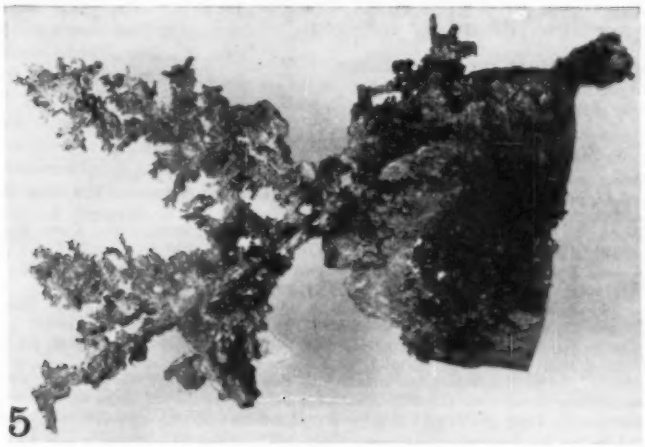

FIG. 5. Dendrite of native copper, formed upon sericitic schist. Su Spilloncargiu section, 410 level. Natural scale.

outcrop is the most superficial part, from which nearly all the minerals were leached, with the exception of ferriferous salts. The minerals found in the outcrop zone are therefore chiefly limonite and subordinately other oxidized minerals such as hematite and melanterite, together with crystalline and colloidal ferriferous oxides and hydroxides.

Oxidation Zone.—The oxidized zone immediately underlies the ferriferous outcrop and into it migrated the metallic non-ferriferous sulfates,where they became fixed to form many oxidized minerals such as oxides, carbonates, sulfates, phosphates, silicates and others. The chief minerals found in this zone are: arsenite, cerussite, anglesite, phosgenite, calamine, malachite, azurite, brochantite, and limonite, together with some oxidized minerals of lead and arsenic (mimetesite), lead and copper (linarite), copper and arsenic (olivenite), iron and arsenic (pitticite).

Enrichment or Cementation Zone.—In the enrichment zone there were deposited supergene sulfides and native metals, consisting of covellite, chalcocite, and native copper, formed by the well known supergene sulfide chemical reactions (1).

I found some beautiful dendrites of native copper in the cementation zone of the St. Clarice stoping works (at the Su Spilloncargiu section) (Fig. 5).

ACKNOWLEDGMENTS

I wish to express my thanks to Soc. Rumianca which allowed the visits to the mine and the publication of this paper. With the favor and the assistance of the Society staff I was enabled to study and describe this particular mineral deposit which is of scientific interest, and also of practical interest, because the output of the two ores is not to be neglected in Italy where raw materials are not numerous.

SCUOLA MINIERE DEL POLITECNICO,
TORINO, ITALIA,
April 2, 1958

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Economic Geology
Vol. 53, 1958, pp. 877–886

SCIENTIFIC COMMUNICATIONS

COLD ACID EXTRACTION OF COPPER FROM SOILS AND SEDIMENTS—A PROPOSED FIELD METHOD[1]

F. C. CANNEY AND D. B. HAWKINS

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ABSTRACT

A rapid field method for the determination of readily-extractable copper in soil and sediment has been developed for use in geochemical prospecting. A 0.2 g sample is treated with 1 ml of cold 6 N hydrochloric acid for 30 seconds; the copper that is extracted is estimated by means of 2,2′-biquinoline in an isoamyl alcohol extract. A sensitivity of 1 ppm is obtained when a 0.2 g sample is used. The percentage extraction is usually great enough to give a positive test on most background materials, a desirable feature.

Because a single determination takes only about 2 minutes and requires only simple, easily portable items of equipment, the method is well adapted to use under rough field conditions—at the sample site if desired. Advantages over a modified dithizone procedure for citrate-soluble copper are the much greater relative stability of the biquinoline reagent and copper complex under field conditions, and the fact that biquinoline is specific for copper.

Since 1955 the method has been tried on several hundred samples of soil and sediment from various localities in the United States with generally excellent results; the only serious interference encountered was in samples containing considerable amounts of decomposing organic matter.

It is suggested that this may be a useful method for those prospectors who are trying to find and outline economically important dispersion patterns of copper in soil or sediment.

[1] Publication authorized by the Director, U. S. Geological Survey.

INTRODUCTION

One of the more widely used field methods in geochemical prospecting during the past few years has been Bloom's procedure (2) for determining ammonium citrate-soluble heavy metals with dithizone. This is a technique for rapidly determining, at the sample site if desired, whether soil or sediment samples contain anomalous amounts of heavy metals (principally zinc, lead, and copper). A small portion of the fine fraction of a sample is shaken with a combination of two solutions—cold [2] ammoniacal solution of ammonium citrate mixed with a lesser amount of dithizone in xylene. If a mixed color is produced in the xylene layer, additional dithizone solution is added until a blue or blue-gray endpoint is reached; the volume of dithizone required to accomplish the color change is roughly proportional to the amount of metal extracted from the sample by the citrate solution.

Even though this method usually measures less than 10 percent of the total heavy-metal content of a sample, the pattern of analytical data revealed by its use is often as enlightening as that brought out by more rigorous methods of sample digestion, and sometimes more so. Because significant results can and have been obtained by this method, and because a determination takes less than one minute and requires a minimum of equipment, the method has been widely accepted by geochemical prospectors. The investigation described by Hawkes and Bloom (3) is one example of the use of this method in geochemical reconnaissance.

Need for a Cold Copper Method.—In spite of its many advantages, this procedure for citrate-soluble metals is not without some disadvantages. The variable sensitivity of dithizone to different metals at a pH of 8.5, the usual pH of this method, is one of the more important disadvantages and the one most relevant to this paper: in reaction with the three most common heavy metals, dithizone is most sensitive to zinc and less so to copper and lead. Another drawback is the instability of dilute solutions of dithizone. Admittedly, considerable progress has been made in the selection and purification of lighter-than-water organic solvents for use in this method, but this potential and often erratic instability is still an objectionable feature.

There are areas, however, where the geochemical dispersion pattern of copper alone is of economic interest, the zinc content of the samples being only slightly, if at all, related to mineral deposits. In such areas, the lesser sensitivity of Bloom's method toward copper may provide data that are hard to interpret; in fact, should the background zinc content of such samples vary widely, it is possible that an important copper anomaly could be completely masked. For this reason geochemists have sought a method with the advantages of the citrate-soluble heavy metals test but specific for copper.

Previous Work.—Considerable experimentation by various groups for the purpose of producing a cold method specific for copper has taken place during the past several years. As the specificity of dithizone for various metals can be controlled to some extent by adjusting the pH of the solution to be ex-

[2] "Cold" is used here, as it is in the remainder of the paper, to mean an ambient-temperature solution.

tracted, the easiest and most obvious modification of Bloom's procedure to make it more specific for copper is to lower the pH of the citrate buffer to about 2–3, where lead and zinc no longer react with dithizone.[3] Experimentation to produce a modified method of this type and descriptions of its trials in the field have been given by Holman (4, 5, 6).

Background of Present Test.—In 1955 Almond (1) of the U. S. Geological Survey published a rapid field and laboratory method for the determination of copper in soils and rocks, based on the reaction between copper (I) and 2,2′-biquinoline to form a pink compound. This method involves fusion of the sample with potassium bisulfate and estimation of copper with biquinoline in an isoamyl alcohol extract. Advantages of this method over the dithizone procedure for copper include (1) the greater stability of the reagent and the copper complex, resulting in stability of the standards for many months; (2) specificity of biquinoline for copper; and (3) greater range of the standard series.

In late 1955, one of us (FCC) while working in the Copper Belt of Vermont, experimented with Almond's method in an attempt to produce a simple cold procedure for copper. Such a method was desired because in that area the geochemical dispersion pattern in soils overlying copper ore is predominantly that of copper. A simple modification that seemed to give satisfactory results involved extracting the copper from a soil or sediment sample with cold 6 N hydrochloric acid instead of by a fusion; this extraction was followed by Almond's standard procedure. This modified method has been tried during the past two years on soils and sediments from a considerable number of localities in the United States with generally excellent results. We thought it worthwhile, therefore, to bring this suggested scheme to the attention of those geochemists who have need of a cold copper method so that they could compare its merits with those of the modified citrate-soluble metals test as described by Holman (4, 6).

REAGENTS AND APPARATUS

The instructions that follow for the preparation of the requisite reagents are modified from Almond (1, p. 4).

Biquinoline reagent (0.02 percent, weight/volume): Add 0.2 g of 2,2′-biquinoline to about 900 ml isoamyl alcohol in a beaker. Warm on a hot plate in a well ventilated area away from open flames until the biquinoline is dissolved. Allow solution to cool and dilute to 1 liter with isoamyl alcohol. The solution should be colorless; if it is yellow, the reagent is impure and should not be used.

Buffer solution: Dissolve 400 g of sodium acetate, 100 g of sodium tartrate, and 20 g hydroxylamine hydrochloride in 1 liter of demineralized water. To check for copper contamination place 10 ml of the solution in a culture

[3] Several other metals such as gold, mercury, palladium, and silver do react at this pH but ordinarily cause no interference because of the scarcity of these elements in most soil and sediment samples.

tube, add 1 ml of the biquinoline reagent, cap and shake for two minutes. Absence of a pink coloration in the organic layer indicates that the solution is satisfactory for use.

Hydrochloric acid, 6 N (1 + 1): Add 500 ml of concentrated hydrochloric acid to 500 ml of demineralized water.

Standard copper solution, 100 micrograms of copper per milliliter: Dissolve 0.2 g of copper sulfate ($CuSO_4 \cdot 5H_2O$) in a small volume of 0.1 N hydrochloric acid and dilute to 500 ml with 0.1 N hydrochloric acid. More dilute standard copper solutions can be prepared by dilution of appropriate amounts of this standard with 0.1 N hydrochloric acid.

Almond directs that the hydroxylamine hydrochloride be added in crystalline form directly to each sample, but it is now standard practice in Geological Survey laboratories to incorporate this compound into the "buffer" solution where it is apparently quite stable; one batch of buffer solution with included hydroxylamine hydrochloride has remained stable in our laboratory for four months. In any event, use of a standard sample as recommended later would reveal any serious deterioration.

The buffer ingredients as described originally are sodium acetate and sodium potassium tartrate; however, sodium tartrate is equally satisfactory in place of the sodium potassium tartrate and is also slightly more soluble. Because these compounds often contain excess acid or alkali, this buffer may have any pH from 4 to 9, but often is about 6. Our work has verified the work of previous investigators that in the pH range from 4 to 9 the recovery of added copper is complete; however, we suggest that the pH of the buffer be checked and adjusted if necessary with HCl or NaOH solutions, so that after addition of the buffer to the acid solution, the extraction takes place in the pH range from 5 to 7. One ml of 6 N (1:1) HCl, the amount suggested for use in this test, when added to 10 ml of the buffer (pH 6.3) drops the pH to 5.2.

Minimum equipment required to perform this method at the sample site would be the following:

1 volumetric scoop, approximately 0.2 cc capacity. Such a scoop will usually measure about 0.2 g of the fine fraction of most soils or sediments.
1 polyethylene dropping bottle, 2 oz, with attached cap, for the 6 N hydrochloric acid. Determine number of drops to equal 1 ml.
1 polyethylene dispensing bottle, 4 oz, for the biquinoline reagent.
1 polyethylene dispensing bottle, 16 oz, for the buffer solution.
1 culture tube, without rim, 22 × 175 mm, marked at volumes of 11 and 13 ml.
1 polyethylene stopper for above culture tube.
1 plastic standard rod.

There are many combinations of equipment that could be used at the sample site to dispense the reagents; the above list is merely one example of a suitable combination. The equipment listed above would hold sufficient reagents for about 40 to 50 determinations.

Although the regular screw-cap culture tubes can be used, the polyethylene caps used on them are often hard to remove and sometimes do not seal tightly. Consequently we now prefer to use threadless 22 × 175 mm culture tubes which can be capped by tapered polyethylene stoppers.

No attempt has been made to provide a list showing the items of regular chemical equipment such as pipettes, beakers, balance, flasks, etc., that are required to prepare the reagents and standards; if needed, this information may be found in the original publication by Almond (1).

PROCEDURE

Place 0.2 g (or one 0.2 cc scoopful) of a soil or sediment sample in a culture tube, add about 1 ml of cold 6 N (1:1) hydrochloric acid, and slosh the sample about in the acid for about 30 seconds. Add 10 ml buffer solution, 2 ml of biquinoline reagent; then cap the tube, and shake vigorously for about 30 seconds. Allow to stand for a few seconds until the isoamyl alcohol layer separates sufficiently, then compare with copper-biquinoline standards. To convert to parts per million [4] multiply by five the number of micrograms of copper found. A standard should be run at the start of each day's work as a check on the reagents and liquid standards (if used) to insure comparable results from day to day.

A series of copper standards for 0, 0.2, 0.4, 0.8, 1.5, 3, and 6 micrograms of copper is recommended. In a field laboratory, liquid biquinoline standards in culture tubes are satisfactory; the use of artificial standards for sample-site analysis will be discussed in a later section. The pink copper-biquinoline complex is very stable, and one set of liquid standards may be used for several months provided the tubes are kept tightly capped to prevent evaporation of some of the isoamyl alcohol and resultant intensification of the color. To prepare liquid standards, place 1 ml of 6 N hydrochloric acid in each of a series of culture tubes; then add to each the required amount of standard copper solution to produce the series suggested above and follow the regular procedure starting with the addition of the buffer solution.

Discussion.—In the base camp laboratory the sample should be dried and sieved and the fines used for analysis. What size fraction of the soil or sediment will best reveal the chemical pattern associated with metalliferous deposits should, of course, be determined experimentally in the area under investigation; the minus 80 mesh and the minus 200 mesh fractions, however, are two sizes in common use in this type of work that have given satisfactory results. For on-the-site use, no sieving is done, but a scoop of the finest portion of the sample should be selected. Because there is usually a roughly inverse relationship between grain size and content of extractable metal, an effort should be made to collect material as comparable as possible in grain size and composition. In on-the-site sampling and analysis of stream sediments, the finest material available may still be so coarse that insufficent copper

[4] When a scooped sample is used, the concentration is actually in micrograms per cubic centimeter. As the bulk density of sieved soil or sediment samples is often about one, however, the resulting value is a fair approximation of micrograms per gram (parts per million).

will be extracted to give a positive test when a 0.2 g sample is used. Here, to increase sensitivity, if desired, the sample size could be increased with the amounts of acid and buffer increased proportionally. Conversely, for samples with high contents of extractable copper the range of the method can be extended by decreasing the sample size to 0.1 g or by increasing the volume of biquinoline reagent. In such cases, of course, different factors would have to be used for conversion from micrograms of copper found to parts per million.

When the tube is shaken, the isoamyl alcohol layer will usually become somewhat turbid because fine solid particles from the sample and water droplets become suspended in the alcohol. This turbidity possibly may bother some analysts, when comparisons with the clear standards are made, but we have not found it too great a hindrance. A few drops of acetone or ethyl alcohol added to the alcohol layer may be of some help in breaking up this emulsion.

Interference from Organic Matter.—The most serious interference yet encountered in trials of this method was with samples containing considerable amounts of decomposing organic matter, such as muck and humus samples. When these samples were extracted, a yellow hue would occasionally appear in the alcohol layer, sometimes of sufficient intensity to interfere with the copper determination. Although we have not investigated the composition of this yellow compound, it seems that the color may be due to solution of part of the organic matter by the alcohol, and not due to a decomposition product of the biquinoline reagent caused by nitrogenous compounds in the organic matter.

We salted some of the samples that yielded strong yellow hues with various known amounts of copper and ran them through the procedure. Although precise comparisons with standards could not be made, there was no difficulty in detecting those samples that contained appreciable amounts of copper. We believe, therefore, that in actual use this type of interference would not cause a highly anomalous sample to be missed.

In some samples, accumulation of relatively coarse organic debris at the water-alcohol interface also interferes; in such cases it was found that the debris could be removed from the interface and dispersed throughout the volume of buffer by manually centrifuging the tube for a few seconds.

Thus, in general, unless the majority of the samples of a geochemical survey contain appreciable quantities of decomposing organic matter, we believe that this potential interference should not deter one from using his method.

PREPARATION OF ARTIFICIAL STANDARDS

One of the advantages of the citrate-soluble-metals procedure is the fact that no standards are required, because a titration with the dithizone reagent is used to estimate the amount of metal extracted. Because the biquinoline reagent used in this test is colorless no such scheme is possible, and it is necessary to use standards if quantitative values are to be recorded. Although it is not inconvenient to prepare and use a conventional series of liquid stand-

ards in a base-camp laboratory, the necessity of juggling seven standards when analyzing samples at the site of collection would tend to make this method less than popular among field men. In order to reduce equipment which the field man must carry, we have therefore attempted to produce artificial standards. The first attempt, which proved satisfactory although not the best, was preparation of a color chart by painting squares on a piece of white cardboard to match the colors in the standard tubes; such a chart should not be used, of course, with tubes of any other size. Any good quality water-color or oil artist's paint is suitable.

One disadvantage of using such a color chart is that it is necessary to compare the intensity of color in a three dimensional layer of liquid against a flat surface. For that reason we have experimented to see if artificial standards could be produced that would permit comparisons to be made under similar geometrical conditions. As a result of this experimentation it seems feasible to prepare and use as artificial standards plastic rods in which, separated by layers of clear plastic, are stacked colored plastic discs that in hue and intensities match the appropriate natural standards. We use a thermosetting, transparent casting plastic that is widely used in the arts and crafts. At room temperature it is a water-clear syrupy liquid that pours easily and sets to a crystal-clear solid that is extremely durable and resistant to heat and chemicals. By combining mixtures of the various standard dyes and pigments that are commercially available for coloring the liquid plastic, it is possible to match the color of practically any standard. Because it seems that artificial standards of this type may have considerable use in geochemical prospecting, a short note on the preparation of such standards will be published separately.

For copper standards, by casting in a 22 × 175 mm culture tube we have prepared rods of this plastic in which are incorporated, one above the other, 6 colored discs that match the copper-biquinoline standards in hue and intensity. To check the stability of these standards in sunlight, we exposed one plastic rod of standards continuously to the weather for one month; at the end of this period the only change noted was a slight yellowing of the clear plastic.

The main advantage of this type of standard is the elimination of 6 of the 7 tubes that would otherwise be required. Using such a plastic rod in the field, all the analyst has to do is to slide the tube containing the unknown alongside the standard rod until a match is obtained. Because the comparisons are made under similar geometrical conditions, they are as precise as if actual liquid biquinoline standards were used.

APPLICATION OF THE METHOD

Since late 1955 the cold extraction method has been tried on several hundred samples of soil and sediment from various localities in the United States. All of these samples were also analyzed by the standard Geological Survey copper procedure which involves decomposition of the sample by a bisulfate fusion, which probably releases most of the copper in the soil or sediment. An examination of the analytical data obtained by the two different methods

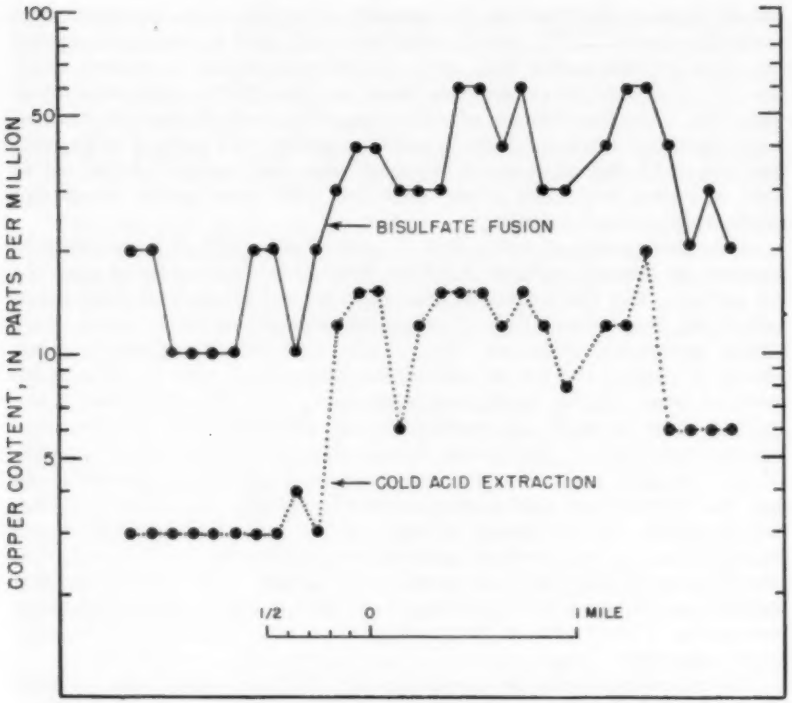

FIG. 1. Comparison of copper content, as determined by bisulfate fusion and cold acid extraction methods, in alluvial soil samples, Basin and Range province, Arizona.

of attack showed that the cold acid extraction tends to remove, on the average, about 10 to 30 percent of the total copper in a sample, although the actual range may be from one or two percent to as much as 50 percent. The percent extracted is of course dependent on a number of important factors such as the fineness of the sample and the manner in which the copper occurs in the soil or sediment. Because it is possible under favorable conditions to measure 0.2 microgram of copper, the method thus has a limiting sensitivity of 1 ppm when a 0.2 g sample is used. This means that a positive test can be obtained on most background materials, a desirable feature.

Two examples of anomalies obtained by the cold hydrochloric acid extraction of soil samples are shown in Figures 1 and 2; comparative total copper values obtained by Almond's procedure are also shown. Figure 1 presents the analytical data of a reconnaissance soil traverse, 2.9 miles long, made in the southern part of the Basin and Range province in Arizona. The samples were of soil, commonly calcareous, that has developed from alluvial-fan deposits. The samples were sieved, and the minus 200 mesh fractions were used

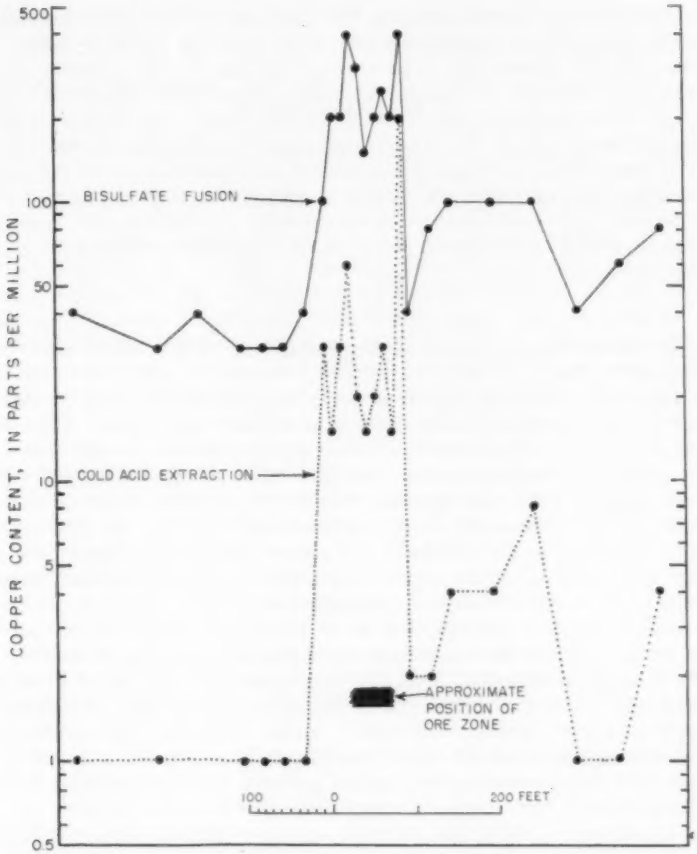

FIG. 2. Comparison of copper content, as determined by bisulfate fusion and cold acid extraction methods, in glacial soil samples, Vermont Copper Belt, Vermont.

for analysis. The data show that the traverse crossed an area containing anomalous amounts of copper and that either method of attack on the sample is satisfactory for outlining the anomaly, although perhaps the pattern as revealed by the cold acid extraction is slightly more homogeneous than that given by the bisulfate fusion method. The main point to be emphasized here is that the faster, simpler cold acid extraction method was just as satisfactory in revealing the copper pattern as the more tedious bisulfate fusion method.

Figure 2 shows the distribution of copper in glacial soil samples collected across a zone of sulfides—chiefly pyrrhotite, but with enough chalcopyrite to make ore—in the Copper Belt of Vermont. The soil samples were collected

from the B horizon, sieved to minus 100 mesh, and the fines used for analysis. Here the comparative copper values reveal a somewhat different picture than in the previous illustration. The average contrast of the anomaly revealed by the cold extraction method is about 25 to 1, whereas the contrast by the bisulfate fusion method is about 8 to 1. Consequently, the dispersion pattern of copper extractable by the cold method is considerably more significant than that of total copper, although either pattern is adequate to reveal the location of the concealed ore zone. Thus this appears to be a good example of the use of relatively weak extractants to partially differentiate the metal in a sample according to its mode of origin, i.e., whether from normal rock or a mineral deposit.

CONCLUSIONS

The modification of Almond's biquinoline copper procedure whereby the sample is treated with cold 1:1 (6 N) hydrochloric acid instead of being decomposed by a bisulfate fusion seems to be a method that may be useful in geochemical prospecting for the analysis of soils and sediments. The method is rapid, requires only simple equipment, and may be used at the sample site if desired. Advantages over a modified dithizone procedure for citrate-soluble copper are the much greater relative stability of the biquinoline reagent and copper complex under field conditions and the fact the biquinoline is specific for copper. The method is not recommended for use where the great majority of samples contain appreciable amounts of organic matter, although it is believed that the off colors resulting from soluble organic matter would not cause a highly anomalous sample to be missed. The method has been tried out on several hundred samples with generally satisfactory results.

It is suggested therefore, that this may be a useful method for those prospectors who are trying to find and outline economically important dispersion patterns of copper in soil or sediment. In any new area, however, the usual orientation studies should be made, if at all possible, to establish that there is a reliable correlation between the mineral deposits and the anomalies revealed by this method.

U. S. Geological Survey,
Denver, Colorado,
June 3, 1958

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Economic Geology
Vol. 53, 1958, pp. 887–893

DISCUSSIONS

URANIUM IN ANCIENT CONGLOMERATES—A REPLY

Sir: In a recent letter to ECONOMIC GEOLOGY, Dr. Schnellman (1) questions whether there is a genetic relationship between the auriferous conglomerates of Ghana and the uranium-bearing bankets of South Africa, and he invites my comments on this much-debated problem. Since I have no new evidence to advance I refrain from expressing an opinion. There is, however, one observation relevant to current discussions which it is pertinent to make.

Whatever may be the origin of the West African mineralization, whether it is argued from the low titanium : iron ratio that it is epigenetic or whether it is claimed from the fineness of the gold that it is syngenetic, there can be no doubt whatever that the gold was deposited in an oxidizing environment. The dominant metallic mineral in the conglomeratic ores of Ghana is haematite and sulphides are rare, whereas the dominant metallic mineral of the Witwatersrand is pyrite and oxides are rare. The West African ores, with a suite of heavy minerals closely akin to those found in many gold alluvials today, will be accepted as fossil placers by many who now have doubts about the syngenetic nature of the South African gold. It is therefore important to observe that the Tarkwaian and Witwatersrand systems in which these auriferous conglomerates occur have long been considered by African geologists to be coeval, and that this traditional correlation has lately been confirmed by geochronological studies (2). It follows that, if these mineralizations are both alluvial, the conclusions of Professor Ramdohr and of the several South African workers who have postulated a reducing atmosphere in explanation of the pyritic bankets demand acceptance of the illogicality that reducing and oxidizing atmospheres existed simultaneously. It would seem that yet another tenet of the placer hypothesis is annihilated by *reductio ad absurdum.*

In the same issue of ECONOMIC GEOLOGY Dr. Brotzen (1) has contributed a letter on uraniferous conglomerates, apparently inspired by the Turgenevian sentiment: "I agree with no man's opinions. I have some of my own!" Whilst it is somewhat difficult to discern precisely what his opinions are, his observations would doubtless have been valuable had they been preceded by a study of the relevant literature. Such prior study would have made it unnecessary for me to point out: (a) that the uraniferous gold-platinum deposit of Ruwe is not the copper deposit of the same name; (b) that the tenor of uranium in Baltic sediments, of which ten recent assays average 4.8×10^{-4} percent, is sufficiently close to the clarke of uranium in the earth's crust (4×10^{-4} percent) to vitiate any extrapolation in consideration of ore-forming processes; (c) that brannerite is not "a rare mineral in spite of prolonged search," but vies tonnage-wise with coffinite (after uraninite-pitch-

blende and carnotite) as the third most important uranium mineral worked in the world today; (d) that it is incorrect to state that "brannerite has not been found as a member of a typical sulfide- or uranium-bearing paragenesis" since there are many Russian and other reports of brannerite co-existent with uraninite, pitchblende and sulphides in igneous and metamorphic rocks; and (e) that in several publications it is on record that the Tarkwaian ores of Ghana are devoid of significant uranium.

Concerning the Witwatersrand thucholite, Dr. Brotzen writes: "That the carbon may be indigenous to the bankets is much more probable than the belief [*sic*] that it is derived from overlying carbonaceous beds"—but he supplies no evidence in support of this view and no informed contradiction of the evidence to the contrary. Had he suggested a mechanism within the bounds of the placer hypothesis whereby hydrocarbon of specific gravity 1.5 or less could become preferentially concentrated along with the heaviest minerals, then his contribution would indeed have been of interest. A further lack of factual support is seen in his postulate that in desert and tropical terrains deoxygenation of vadose waters may initiate a reducing environment at shallow depth where pyrite can form. That sulphides may locally survive as detrital minerals in gravel beds or may sometimes be formed there authigenically is common knowledge; but no rational explanation has been forthcoming from the placerists to tell us how oligomictic quartz-pebble gravels can become syngenetically mineralized with from two to twelve percent pyrite, and significant uraninite, simultaneously over an area of many tens of thousands of square miles. Dr. Brotzen's "analogies with actualistic conditions in western Africa" suggest that he might with profit read the reports on what has actually been found there. For example, in Sir Albert Kitson's detailed examination (3) of 586 mixed alluvial concentrates of Recent date from the Gold Coast, 395 were found to contain identifiable gold but only 12 yielded pyrite. Later studies of the same concentrates showed that none contains uraninite.

In the first paragraph of his letter, Dr. Brotzen comments that "our knowledge . . . of hydrothermal processes is rudimentary in comparison to what is known about sedimentation." He echoes in some part remarks which I made in 1953 (4). "It is abundantly clear from first principles that the uraninite, and therefore the gold, is not of placer deposition. To assert on present knowledge that the deposits are of a hydrothermal character is merely to frame the same conclusion in less precise terms, and a positive statement of this kind must remain of little value until it becomes possible to picture, with supporting evidence, some feasible means whereby the epigenetic mineralization was accomplished. Unfortunately, although a great deal about the formation of placer deposits of all kinds is known, knowledge of the mechanism of hydrothermal ore genesis is distressingly scanty." But I should certainly not write quite so modestly about our knowledge of hydrothermal mineralization today. In the paper under discussion (1), I suggested that the genesis of the Witwatersrand ore could be linked to the post-Transvaal earth movements associated with the Vredefort and other domes and with the Bushveld granites—a view more tentatively expressed in my earlier writings. This hypothesis has been confirmed with quite startling rapidity, for several inde-

pendent studies of some six South African geochronologists, presented to a meeting of the Geological Society of South Africa in February and now awaiting publication (5), have demonstrated a general identity of age between (a) the Witwatersrand uraninite, (b) a well-crystallized *hydrothermal* monazite present rarely in the banket, and (c) the post-Transvaal Bushveld granite. Late last year it was claimed by Dr. Brock and others (6) that the great age of the Witwatersrand uraninite, in the range 1500–2000 m.y., proved it to be much older than the host rocks and therefore detrital. Today it is known that the overlying Transvaal System is older than 1950 ± 150 m.y., the age of the Bushveld granites which cut it. One cannot but wonder how long this great advance in our knowledge of the stratigraphical history of South Africa would have been delayed had there been no dissension from the placerist doctrines prevailing on the Witwatersrand.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
July 15, 1958

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ON THE URANIUM–THORIUM RATIO IN THE BLIND RIVER, ONTARIO, URANIUM-BEARING CONGLOMERATE

Sir: The Blind River, Ontario, uranium deposits have a counterpart in the Witwatersrand gold–uranium field of South Africa. The origin of the South African gold–uranium deposits has been a subject of controversy for several decades. The two contesting schools are the "placerists" and the "hydrothermalists." The placerists postulate a detrital origin for the gold and uranium, whereas the hydrothermalists assume that emanations from extraneous, probably igneous, sources gave rise to the ore. Scientific investigations have done little to settle the question of origin.

C. F. Davidson, in a recent paper (Vol. 52, p. 668–693, 1957), discusses the origin of the Blind River, Ontario, uranium deposits. He states (p. 683) "field evidence superficially favoring a detrital derivation of the radioactive minerals is flatly contradicted by geochemical thinking." He explains (p. 675–676) "the weaknesses of the alluvial theory lie not so much in past

studies of field geology, . . . , as in interpretation of the fundamental geochemistry of the ores."

Davidson devotes one section of his paper to the "geochemistry of the bankets" in which he discusses both the South African and Blind River deposits. More than half of his discussion of geochemistry is devoted to the genetic significance of the relative abundance of uranium and thorium. Davidson notes (p. 670) that in all normal sedimentary rocks the thorium content is much in excess of the uranium content, "and in highly weathered sediments such as sandstones and conglomerates the thorium–uranium ratio is commonly 10:1 or more" (p. 670). In the Blind River and South African uranium-bearing conglomerates, however, Davidson observes, the uranium content greatly exceeds the tenor of thorium, and, therefore these deposits cannot be considered sedimentary assemblages.

The Blind River Mississagi conglomerate covers many hundreds of square miles. Of this area only a relatively small part holds proven economic uranium reserves and the uranium–thorium ratio varies widely. In the southwestern part of the Camp, in Mack and Scarfe Townships for instance, the thorium content in the conglomerate goes up and the uranium content is low. Typical analyses are as follows[1]: U_3O_8 0.03%, ThO_2 0.10%; U_3O_8 0.01%, ThO_2 0.04%; U_3O_8 0.01%, ThO_2 0.13%. The ThO_2 content therefore exceeds the U_3O_8 content by a ratio of up to 13:1. This falls in line with Davidson's thorium-uranium ratio for alluvial deposits. The size of the area with a high thorium-uranium ratio in the conglomerate is probably large, but there is no known way, at present, to define its limits. Many of the drilling ventures in that part of the Camp were promotional and as no economic uranium grade was discovered, the companies pulled out and only few records of analyses are available.

If the thorium–uranium ratio is a valid criterion attesting to the origin of the ore as Davidson proposes, then the weight of the evidence for at least a part of the Blind River deposits lies with a sedimentary origin for the radioactive mineralization.

GERALD M. FRIEDMAN

RESEARCH CENTER,
PAN AMERICAN PETROLEUM CORPORATION,
TULSA, OKLAHOMA,
May 5, 1958

[1] These analyses were made for the writer by the chemical laboratory of Pronto Uranium mines.

THE SOURCE BED CONCEPT

Sir: C. L. Knight's paper "The Source Bed Concept" (ECON. GEOL., Vol. 52, No. 7) was bound to provoke criticism, especially from the pure epigeneticist who refuses to admit the possibility of a syngenetic origin of some of the larger base metal deposits. In Australia at least, it is already obvious that most of this criticism will not appear in print. The argument

pro and con syngenesis or epigenesis of base metal deposits is not new, but it is in danger of assuming the proportion of such classical arguments as have developed from the theory of continental drift or between the Plutonists and the Neptunists. Perhaps it is worthwhile at this stage to endeavor to put this matter in perspective. This is to state that some deposits are obviously epigenetic; some are just as obviously syngenetic; but between these two groups are a very large number of major deposits that have a syngenetic bias in the regional sense but which in detail have many of the appurtenances of the epigenetic type.

The main difficulties precluding agreement on which type a particular deposit belongs to, seem to arise with those bedded deposits that have been metamorphosed or structurally deformed. In many such cases there has been a tendency to put most emphasis on the evidence derived from a few polished sections rather than on what may have been accumulated by much regional and detailed mapping.

If the many different papers dealing with the Witwatersrand are any guide, full agreement on either of the two main theories of ore genesis is impossible in these cases. However, it is fair to state that the theory or theories of the epigenetic origin of ore deposits has had a long start on its younger rival; it is also fair to state that an increasingly large number of geologists are looking to syngenesis to provide a logical explanation of the features of some deposits that cannot be satisfactorily explained by other means. The epigenetic origin of some vein type deposits or porphyry copper deposits for example cannot be seriously questioned, but in regard to bedded deposits, or those that show strong evidence of a stratigraphic control, the epigenetic theory has some serious drawbacks. Chief among these is a satisfactory explanation of a mechanism whereby the ore minerals were emplaced in their present position and the means whereby they were transported from a magmatic source which may have been several miles away. One often reads the hackneyed term "replacement" but in how many cases does the user of such a term know the details of the replacement—what rock-forming minerals are present in the replaced material and whether it is physically and chemically possible to replace them by particular sulfides? An example that may be used to highlight this problem is the large lead-zinc orebody at Mount Isa in Queensland. This deposit is stratigraphically controlled, is situated in practically unmetamorphosed sediments and is some four miles distant from the nearest granite outcrop. The ore consists of beautifully banded sulfides including pyrite, sphalerite and galena. These are arranged in layers in a shale composed essentially of siltstone and cherty dolomite. The sulfide layers are not arranged in any particular sequence and range from minute bands up to about two inches in thickness. They faithfully follow the outlines of primary sedimentary structures such as small slump nappes. There are some minor veinlets of sulfides that transgress otherwise barren bands in the ore.

A theory of epigenetic origin for this deposit needs to explain a truly remarkable fractionation of a hydrothermal fluid containing mixed elements, and the delivery of different sulfides to the country rock in such a way as to retain its sedimentary characteristics. The fluids need to "intimately replace"

. . . favorable bands" in this country rock. I personally am unaware of any evidence of a chemical rock environment that could support a favorable band hypothesis for each of the ore-mineral layers; and I cannot conceive either the original fractionation or the means whereby the magmatic "juices" travelled from source to orebody. The minor veinlets crosscutting the barren bands I can imagine as being formed by later migration of previously deposited sulfides into fractures developed during tectonic movement. It is also conceivable that this could happen on a larger scale.

Blanchard & Hall (1) accept an epigenetic origin for the Mount Isa deposits. They state that the age of the Mica Creek pegmatite would be "strong presumptive evidence" for a similar age of the Mount Isa ore. The pegmatite age is quoted by Kulp (2) as $933 \pm 12 \times 10^6$ years, but a recent and, it is emphasized, preliminary determination on Mount Isa galena shows an age of about $1{,}600 \times 10^6$ years.[1]

The syngenetic theory as applied to this particular deposit at least has the virtue of obviating the major problems inherent in any explanation of magmatic origin. In other words the sulfide layers can be regarded as any other chemical or biochemical deposit, and the problem of emplacement is greatly simplified. For those of us who ponder about the volume of base metal present, it is perhaps worthy of note that our marine biologist friends are now not in the least worried about his particular aspect.

The Rum Jungle uranium deposits point up the problem in a different way (3). Here the nearby Rum Jungle granite has been long proposed as an obvious source of the ore deposits. The regional geology indicates a marked stratigraphic influence very much in favor of a syngenetic origin. The orebodies are in Lower Proterozoic sediments, mainly carbonaceous siltstones with associated dolomitic rocks: but they are localized on Upper Proterozoic structures. Age determinations show the granite to be about 1,200 million years older than the ore. The orebodies are in a very restricted Lower Proterozoic sedimentary environment and in unmetamorphosed rocks. There is no evidence whatsoever of upper Proterozoic vulcanism or igneous intrusion in this area and one is more or less forced to the conclusion that the uranium was deposited with the sediments and later migrated to its present loci. The migration may perhaps have been caused by the energy environment induced by the late Proterozoic faulting. This theory can no more be substantiated by precise physical data than can a hypothetical "telemagmatic" source of the ore, but in my opinion it is more logical as at least one can see most of the syngenetic requirements. For a magmatic origin one must literally delve into the depths.

Most orebodies are structurally controlled. Such structures can be regarded as favorable loci for the accumulation of magmatically derived metals; but they can also be regarded as evidence of a pre-existing energy environment induced by stress and in which the structure itself constitutes a zone of low potential energy, which surrounds a zone of high potential energy. Fluids will tend to move towards the zone of low potential energy. Perhaps syn-

[1] Determination by Dr. J. Richards, Australian National University—personal communication.

genetically derived sulfide minerals might do the same and again perhaps this is one reason why so many orebodies have some of the characteristics of both syngenetic and epigenetic types.

Our problem, therefore, is not a simple matter of epigenesis versus syngenesis, but rather lies in the mechanism or mechanisms whereby metals migrate in or from source beds or from magma; in determining and being able to recognize those sedimentary environments that are the most favorable loci for the accumulation of metals of syngenetic origin. The epigenetic theory has been developed by a very large number of first-rate geologists over the years—the syngenetic theory is only now gaining momentum. But a considerable number of metalliferous geologists have had little practical training in the fundamentals of sedimentation or in determining, for example, the spatial position of a particular ore-bearing facies assemblage in a geosynclinal pile. Recognition of such features is essential if the syngenetic theory is ever to be adequately documented. Mt. Isa again may be used as an illustration here. Blanchard & Hall (1) did not recognized that most of the crenulations and breccias described by them are, in fact, magnificent examples of primary slump structures.

Mr. Knight's paper does not state, but certainly infers, that we must extend our search for new deposits beyond the empirical limits placed on it by strict adherence to an epigenetic theory of the origin of base metal deposits. With such an inference I am personally in full agreement.

I cannot agree with Mr. Knight's statement, which has been pointed up by Chamberlain (ECON. GEOL., Vol. 53, No. 3) that

> "If the orebodies of the fields listed in this paper are basically sedimentary in origin, then it is logical to argue that all sulfide orebodies, with the possible exception of some magmatic segregations, were derived from original sedimentary accumulations of sulfides."

This statement needs qualification to make it acceptable but in general Mr. Knight's paper is of real value in that it has stimulated discussion on a topic that has long occupied the thoughts of a number of metalliferous geologists. It is a great pity that so few of the "campfire arguments" on a subject such as this find their way into print.[2]

B. P. WALPOLE

BUREAU OF MINERAL RESOURCES,
CANBERRA, AUSTRALIA,
July 22, 1958

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[2] Published by permission of the Director, Commonwealth Bureau of Mineral Resources, Geology and Geophysics.

Economic Geology
Vol. 53, 1958, pp. 894–905

REVIEWS

FIFTEEN REVIEWS OF RECENT RUSSIAN LITERATURE ON ECONOMIC GEOLOGY

The following books not hitherto noticed in ECONOMIC GEOLOGY, among others, have been received by the reviewer since mid-1957. Works of which publication has not yet been completed are denoted by an asterisk. Of the few periodical publications listed, most are new journals concerned with economic geology.

Mednoe mestorozhdenie Kounrad. (The copper deposit of Kounrad.) BY K. S. GAZIZOVA. Pp. 130; pl. 13, Gosgeoltekhizdat, Moscow, 1957. Price, 5r. 60k. (Paper covers.)

Kounrad is a large copper-molybdenum deposit of porphyry-copper type near Balkhash, in the Karaganda oblast. Investigation shows that the so-called mineralized stock is but a marginal sector of a huge massif of granodiorite; that an extensive development of fluidally-banded extrusive quartz-porphyry post-dates this batholith; and that the mineralization with accompanying silicification stems not from the intrusion but from the reservoir whence emanated the extrusive rocks. [Structurally and mineralogically the deposit shows strong resemblances to Climax, Colorado.]

Geologicheskoe stroenie i zheleznye rudy Krivorozhskogo basseina. (Geological structure and iron ores of the Krivoi Rog basin.) Edited by YA. N. BELEVTSEV. Pp. 279; figs. 85. Gosgeoltekhizdat, Moscow, 1957. Price, 21r. 15k.

The three-dimensional geology of this famous iron ore complex in the crystalline rocks of the Ukraine has been delineated in great detail from more than 6000 borings undertaken in the last 25 years, many to depths of over 1000 meters. This monograph, a composite work by 14 authors and many collaborators, gives a well-planned and lucid account first of all of the geology of the Krivoi Rog basin (142 pp.) and then of the iron ores and the ore deposits themselves (120 pp.). According to the bibliography at least 250 works have been published on the geology of the field.

Materialy po geologii i metallogenii Rudnogo Altaya. (Contributions to the geology and metallogeny of the Rudnyi Altai.) Pp. 187; pl. 9. Gosgeoltekhizdat, Moscow, 1957. Price, 14r. 65k.

The volume embraces a dozen articles on the geology and mineralization of this important ore-field, where the main deposits are of blende-galena-chalcopyrite-pyrite type with a by-production of gold and silver as native metals and as tellurides. Mineralogical studies have been carried out at some 40 mines.

Geologiya Leninogorskogo i Zyryanovskogo rudnykh polei na Altae. (Geology of the Leninogorsk and Zyryanovsk ore fields in the Altai.) Edited by K. I. Satpaeva. Pp. 371. Gosgeoltekhizdat, Moscow, for Kazakhstan Academy of Sciences, 1957. Price, 25r. 35k.

A report of investigations from 1948 to 1954 in the two principal ore fields of the Rudnyi Altai, with special emphasis on the genesis of the polymetallic ores. The host rocks range from Silurian to Lower Carboniferous in age but are dominantly Middle Devonian sediments, lavas and pyroclastics; and the mineralization, in veins, disseminations, and massive replacements, stems from various stages of Variscan granitization and tectonogenesis.

Geologiya i voprosy genezisa polimetallicheskikh mestorozhdenii Priirtysh'ya. (Geology and genetic problems of the polymetallic deposits of Pri-irtyshia.) By P. F. Ivankin. Pp. 248. Gosgeoltekhizdat, Moscow, for Kazakhstan Academy of Sciences, 1957. Price, 18r. 10k.

The Pri-Irtysh sector of the Rudnyi Altai is a large mining district which has recently seen more than 150 development projects, of which around 10 have furnished mines of polymetallic ores. This informative description of the principal occurrences is accompanied by geological sketch-maps and sections. Of 174 known mineral prospects, 9 are tourmaline veins with copper and gold, 29 are iron-copper sulphide skarns, 57 are polymetallic sulphide occurrences and 79 are quartz-copper and quartz-barytes-lead-copper veins.

* **Mineralogiya polimetallicheskikh mestorozhdenii Rudnogo Altaya.** (Mineralogy of the polymetallic deposits of the Rudnyi Altai.) In three volumes. Vol. ii. Pp. 424, figs. 115, tabl. 185. Kazakh Academy of Sciences, Alma-Ata, 1957. Price, 36r. 75k.

Only one of the three volumes has yet been received. The work is a regional mineralogy by six authors, with a good deal of new chemical and X-ray data.

Voprosy geologii agronomicheskikh rud. (Contributions to the geology of agronomic ores.) Pp. 240. Academy of Sciences, Moscow, 1956. Price, 15r. 15k.

A symposium of 20 papers, of which nine deal with deposits of phosphorite, six with potash salts, and one with boron compounds in the Soviet Union. The phosphorites reputedly of sedimentary origin include pre-Cambrian apatite-gneisses interbedded with metamorphic marbles and quartzites in the Slyudyanka district of southern Pri-Baikalia.

Khrystalenosnye kvartsevye zhily i ikh genezis. (Veins of quartz crystal and their genesis.) By E. M. Laz'ko. Pp. 205, figs. 54; pl. 14. University Press, Lvov, 1957. Price, 10r.

A description of the deposits of rock crystal and piezocrystalline quartz worked in the Aldan massif, with special reference to their mineralogy and conditions of formation.

Trudy Laboratorii Geologii Uglya. (Transactions of the Laboratory for the Geology of Coals.) Vol. 7. Pp. 238 + folding maps and tables. Academy of Sciences, Moscow, 1957. Price, 18r. 45k.

In a collection of 20 papers, deriving from a Conference on Coalfield Geology held at Leningrad in 1955, an account is given of some of the principal coal basins

of the U.S.S.R. The chief workable coals occur in strata of Devonian, Carboniferous, Permian, Jurassic (Lower, Middle and Upper), Cretaceous (Lower and Upper) and Tertiary age.

Ispol'zovanie geobotanicheskogo metoda pri geologicheskikh i gidrogeologicheskikh issledovaniyakh. (The use of geobotanical methods in geological and hydrogeological investigations.) By S. V. Viktorov. Pp. 199; figs. 35. Academy of Sciences, Moscow, 1955. Price, 9r. 80k.

An introduction to the use of plant ecology in surveying (including aerial surveying) for mineral deposits and particularly for water. Reference is made to more than 400 plants. Of the 340 items in the bibliography, 290 are in Russian.

Obshchie printsipy regional'nogo metallogenicheskogo analiza. (General principles of regional metallogenetic analysis.) Pp. 150, + tables. Gosgeoltekhizdat, Moscow, 1957. Price, 8r. 20k.

In the U.S.S.R. much use is made of prognostic metallogenetic maps which, by interpreting the geological structure to show the most probable distribution of mineralization, serve as a practical basis for prospecting operations. In this publication eight authors review the problems of classification of ore deposits in connexion with the production of such maps, and give an interesting summary of the different kinds of ore deposit in Soviet territories. There is no mention of uranium ores.

Geokhimiya redkikh i rasseyannykh khimicheskikh elementov v pochvakh. (Geochemistry of the rare and dispersed chemical elements in soils.) By A. P. Vinogradov. Pp. 238. 2nd edition. Academy of Sciences, Moscow, 1957. Price, 15r. 70k.

At the request of the U.S.S.R. Ministry of Geology this work on the tenor and distribution of the trace elements in soils (first published in 1950, with a German translation in 1954) has been rewritten to include the latest researches of the Vernadsky Institute of Geochemistry and other establishments. The bibliography from which the text is culled extends to some 550 items, one-fifth of these being in the Russian language.

Metodika geologicheskogo kartirovaniya metamorphicheskikh kompleksov. (Geological mapping methods for metamorphic complexes.) Edited by V. A. Nikolaev. Pp. 451; figs. 224. Gosgeoltekhizdat, Moscow, 1957. Price, 25r. 10k.

The title is somewhat of a misnomer, since this work is essentially a symposium by six authors on varied aspects of metamorphism in relation to stratigraphy, structure, tectonics and magmatism. The text merits translation, for most of its succinct descriptions of metamorphic rock complexes are drawn from Russian literature little known in the West. It is sponsored by the "Laboratory for the Geology of the Precambrian."

Metodicheskie ukazaniya po proizvodstvy geologo-razvedochnykh rabot. (Systematic instructions for the execution of geological-prospecting work.) Gosgeoltekhizdat, Moscow, 1957.

Under this title there is published a series of 12 small handbooks, around 100 pages each, designed to encourage prospecting for ore deposits. Typical volumes

are no. 2, on beryllium, tantalum and niobium; no. 10, on copper, lead and zinc; and no. 12, on placer deposits of gold, platinum, tin, etc. The booklets are not illustrated.

Voprosy mineralogii, geokhimii i genezisa mestorozhdenii redkikh elementov. (Contributions to the mineralogy, geochemistry and genesis of rare-element deposits.) Pp. 164. Academy of Sciences, Moscow, 1957. Price, 11r. 60k. (Paper covers.)

A symposium of 18 papers includes contributions on the geochemistry of selenium and of scandium; a group of papers on the mineralogy and geochemistry of the Lovozero and Khibin alkalic complexes; accounts of new varieties of bertrandite, microlite, polycrase and leucophane; a study of trace elements in Siberian traps; papers on rare-element pegmatites; and others. This is the first volume of a new periodical from the Academy's "Institute for Mineralogy, Geochemistry and Crystallography of Rare Elements."

Additional reviews will follow in subsequent numbers.

C. F. DAVIDSON

UNIVERSITY OF ST. ANDREWS,
SCOTLAND,
Aug. 6, 1958

Landslides and Engineering Practice. Edited by E. C. ECKEL. Special Report No. 29, Highway Research Board, National Academy of Sciences—National Research Council, Publication No. 544. Pp. 232; figs. 126. Washington, 1958. Price, $6.00.

Among the many witticisms about committees and their works, the old saying that the one thing a committee cannot do is to write a book is as familiar as any. This is one saying, however, that will now have to go into the discard, for here is a book that is the work of a committee, and it is a good book too. Developed as a result of the work in recent years of the Committee on Landslide Investigations of the Department of Soils, Geology and Foundations, of the Highway Research Board, the volume contains a comprehensive review of current knowledge of landslides, their prevention and correction. It will add still further to the world-wide reputation of the fine work done by the Highway Research Board, made so conveniently available for general use through its growing series of publications.

Although a committee is the titular author of the book, rightfully listed also on the title page is the name of the Chairman and Editor, Edwin C. Eckel, whose skilful work is evident throughout. Chief of the Engineering Geology Branch of the U. S. Geological Survey, Mr. Eckel has brought his wide experience in all phases of engineering geology to bear on the presentation of this review of one of the most serious types of trouble in civil engineering work which can be caused by geological features. Assisting him as authors of the various chapters were all thirteen remaining members of his committee, special tribute being paid (with a fine accompanying portrait) to S. E. Horner, Chief Geologist to the State Highway Commission of Kansas, who died before he could participate in the writing of this book which he had helped to plan. Seven of the authors are engineers; seven, including the chairman, are geologists—a happy combination for such a task as the writing of this volume, and a pattern which one may hope to see reflected in future publications of mutual interest to both disciplines.

The book is divided into two parts. The first, consisting of six chapters which make up exactly half the total contents, deals with the definition of the problem; the second, made up of four chapters, treats the solution of the problem, "the problem" being the occurrence of landslides on engineering works. An introduction by the Editor is followed by a discussion of the "Economic and Legal Aspects" of landslides, probably the most difficult subject of all those covered, the difficulty being reflected in the rather inconclusive treatment. "Landslide Types and Processes" is perhaps the most important chapter of all, presenting as it does a new classification system, illustrated by a lucid chart, a system that may be expected to take the place of that of Sharpe which has been widely used during the last two decades. Succeeding chapters deal with the recognition and identification of landslides, the use of airphoto interpretation in such work, and associated field and laboratory investigations. The second part of the book has chapters on the prevention of landslides and on their control and correction, and a theoretical treatment of stability analysis and the design of control methods. The volume finishes with a succinct review of present trends, which comes to a close, most fittingly, with a quotation from a paper by Chairman Eckel pleading for more published records of the details of actual landslides, upon which further progress in their control can alone be based.

Inevitably, in a book of this sort, there is a certain amount of overlapping and repetition between chapters. It is easy to see, however, that the Editor has done a careful job of trying to reduce such duplication to a minimum, consistent with the fact that each chapter was individually prepared. There is wise cross referencing to some key illustrations, and to the tables, or check lists, which form a valuable supplement to the text. The illustrations, in general, have been particularly well selected, the exceptions being the eleven full page plates of stereo pairs used to illustrate the chapter on airphoto interpretation. Even when reproduced to the high standard shown throughout the volume, they are still of very dubious value, if only because of the small scale used in all cases. This is unfortunate, in view of the great assistance which can be obtained from aerial photographs, assistance that is not very clearly developed by the authors of this particular chapter. Production of the book is commendable and the printing excellent. No misprints were noted but the Editor apparently turned a blind eye to his contributors' weird use of the word "data." The expression "provide better data" turns up at least three times but even it is eclipsed by the "amount of data that should be obtained." Despite the widespread, but unfortunate, indiscriminate use of this most valuable plural noun so directly borrowed from Latin, one might have expected a publication of the National Academy of Sciences to have held the fort against the inroads of this philological philandering.

Much of the information assembled by the Committee came to it through replies to an extensive questionnaire that is reproduced as an appendix. Seventy-five replies were obtained in response to 250 requests. The length of the questionnaire itself makes this response quite a favourable one. With such a mass of information available, it is perhaps not surprising that the Committee gave so much attention to the details of their subject that they do not make as clear in their book as this reviewer considers desirable, or rather essential, the fundamental connection between local geology and the occurrence of landslides. Only by a full appreciation of the fact that subsurface conditions may, and usually will be responsible for the surficial evidence of land movement can any proper understanding of landslides, and so of their prevention or correction, be obtained. This is no carping criticism but a suggestion for a desirable feature of such a book as this which the authors possibly deliberately minimized in their desire

to present a "practical" treatise. Since, however, engineers are all too prone to neglect the geological aspects of their soil and foundation work—until trouble develops—it is to be hoped that this basic feature of landslides may be given more prominence when the second edition of the volume is prepared.

Reference to the distinct possibility of a second edition is perhaps the best tribute which can be paid to the book. It is already so useful a reference volume, not only to the engineer but also to the geologist, that the omission of an index seems to be unfortunate. If an index could be added to future editions, and if the references could be assembled into a full bibliography to serve the whole book (possibly using the bibliography sponsored by the Committee some years ago), the convenience of future readers would be further assisted. Even without these detailed features, this first edition is a notable addition to the literature of engineering geology that should quickly prove to be a standard guide and invaluable reference volume.

ROBERT F. LEGGET

DIVISION OF BUILDING RESEARCH,
NATIONAL RESEARCH COUNCIL,
OTTAWA 2, CANADA,
Aug. 5, 1958

Fundamental Problems in Study of Magmatic Ore Deposits. BY A. G. BETEKHTIN (editor) and others. 2nd edition. Pp. 622; illust. Academy of Sciences of the USSR, Moscow, 1955. Price, roubles 41. (Only in Russian.)

This is a symposium of ten papers dedicated to the theory of ore genesis. Besides the theoretical aspects, the authors intended to prepare a manual designed to help the geologists in exploration of new deposits.

A. G. Betekhtin and F. N. Vol'fson, The history of development of study of ore deposits in Russia (p. 7–81).

The authors begin with a survey of mining operations since prehistoric times, through the period of the Russian principalities, up to the invasion of the Tartars. The new epoch in the development of mining industry, and discovery of new ore deposits in the East, begins in the 16th century. The first copper smelter in the Urals was built in 1635. In 1719 the Board of Mines was founded. M. Lomonosov published in 1757 his book wherein he advocated a plutonic theory of ore genesis. The first school of mines was founded in 1773. A course of economic geology, as a special subject, was taught by A. P. Karpinskii in the early 1880's. The authors list the contribution to the science of ore genesis by Russian geologists over the period of almost 75 years.

A. N. Zavaritskii, The pegmatites as intermediate formations between the igneous rocks and the ore veins (p. 82–95, 1 fig.).

This paper has been already published in "Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva," 1947, no. 1. A system consisting of minerals + saturated solutions (of a composition similar to that of the minerals) results in formation of pegmatite through recrystallization of fine grained rock in a closed system. The author is critical about the existence of a specific pegmatitic magna and advocates the role of a solution that produces recrystallization. This is the same solution that transports from the magma the metallic compounds of the ore veins. The pegmatites are metamorphic rocks that form under conditions of equilibrium between the minerals of the igneous rocks and the residual solution. Progressing further away from the source, the postmagmatic solutions, while reacting with the surrounding rocks, change their composition. With the de-

creasing temperature these solutions form a series of rocks, which is represented by pegmatites, albite and biotite rocks, greisens and micaceous rocks, beresites, sericitized rocks, secondary quartzites, talc-carbonate rocks, and chloritic rocks. It is suggested that the difference in concentration of components across the pegmatite is a possible cause of zoning. The author disagrees with Schneiderhoehn on the difference between the schliers formed by the anatexis and the real pegmatites. According to Zavaritskii, both are formed by the same solutions. The difference is not qualitative but quantitative and depends on the amount of the available pegmatitic solutions.

V. A. Nikolaev, The problem of origin of hydrothermal solutions and the stages of magmatic process at great depth (p. 96–124, 11 figs.).

The features of crystallization of binary and ternary silicate systems with volatile components are presented in an elementary form with reference to the stages of the abyssal magmatic process and the physical chemistry of the hydrothermal solutions. The author stresses the importance of the pneumatolytic stage in the process of crystallization of magma at great depth and magmatic distillation (separation of supercritical solutions preceding the formation of hydrothermal solutions). Referring to the results of experiments accomplished by Goranson, the author considers the principle of the limited solubility of components in the system: rock forming silicate - water. This principle serves as basis for a third type of physico-chemical systems with one critical point on the three-phase diagram. Nikolaev analyzes the ternary system of a mixed type, such as: water - rock forming silicate - particular component (possessing a higher solubility in the supercritical phase of H_2O than the silicates and silica). During the crystallization of deep seated magma, the separation of a gaseous phase does not exclude the possibility of a continuous existence of a liquid phase throughout the whole temperature range. This phase represents the gradual transition from a melt to a hydrothermal solution. Ershov (1) criticizes this paper because of lack of experiments supporting the theoretical conclusions, and failure to consider the form under which the heavy metal compounds exist under magmatic conditions. Ostrovskii (3) thinks that the binary diagram of the 3rd type with one critical point on the three-phase curve is improbable, from the thermodynamical point of view.

A. G. Betekhtin, The hydrothermal solutions, their nature, and processes of ore formation (p. 125–278, 40 figs.).

The regime of sulfur and oxygen in metal-bearing solutions is the principal factor which governs the ore deposition. The interrelation of concentrations of ions of these two elements changes not only because of cooling and reactions with the country rock, but also because of the ascent of the solution to the earth surface. Speaking of the transportation of a substance in hydrothermal solutions, Betekhtin refers to Garrels and Smith, and asserts that the transportation of sulfides in form of solutions is untenable. The "solubility" of the majority of sulfides of heavy metals in colloidal medium is millions of times greater than in a true solution. However, Betekhtin rejects the possibility of transportation of a substance in colloidal form along a considerable distance. Therefore, prior to the formation of crystals, or colloform deposits, the solutions should have been true solutions. A high concentration is necessary. This is possible when easily soluble compounds are available. The ores are difficultly soluble products of chemical reactions and are not the same compounds which have been transported in hydrothermal solutions. Betekhtin disagrees with Goodchild's suggestion about the transportation of mineral matter by means of flotation of sulfides. He doubts that the transportation of chlorides is possible in the gaseous state at great depths

and disagrees on this subject with Fenner. The chlorides and fluorides should have accumulated in postmagmatic solutions within the intrusive body before the development of the hydrothermal stage. The precepitation in form of sulfides is the result of exchange-dissociation reactions. The author analyzes the regime of sulfur in hydrothermal solutions and concludes that, due to cooling, the conditions become more favorable for the chemical reactions of heavy metal cations with the S^{-2} anions and the precepitation of insoluble sulfides. However, the temperature factor is subordinate to the change of concentration of cations of metals and anions of sulfur. Different degrees of oxidation of sulfur are discussed. Betekhtin says that the old principle, according to which each mineral in a hydrothermal solution corresponds to a more or less definite temperature range of formation, is untenable. The regime of oxygen in the earth's crust and its influence on the process of ore formation is described and illustrated with examples of paragenetic associations. The oxidation of certain elements occurs more readily in alkaline solutions. The influence of temperature on the oxidation potential is insignificant. The effect of carbon dioxide on the physico-chemical character of solutions is thought to be important during the late stages of the hydrothermal process. The author says that the hydrothermal solutions were probably weakly alkaline at the moment of their formation. The chemical reactions occurred in weakly alkaline or neutral media. The oxidation of sulfides near the surface could create an acidic medium. The liquid inclusions, evidently, do not represent the preserved remnants of a true ore solution and are products of chemical reactions. The paper is illustrated with microphotographs of polished sections. The paragenetic diagrams of the systems Fe-S-O, Cu-Fe-S, Cu-Fe-S-O, Fe-Ni-S, Fe-Ni-Cu-S, Fe-Ni-S-O, Fe-As-S, Fe-Cu-As-S, and Fe-Sb-S are derived from known studies of paragenetic associations of minerals in several deposits of different genetic types. Betekhtin summarizes with a conclusion that the hydrothermal solutions are genetically related to the cooling intrusives under hypabyssal and abyssal conditions at depths under 11–12 km and pressures below 3,000 atm. The hydrothermal solutions form in intergranular space. The mineral compounds are transported as true solutions, in the form of soluble halogens, boric, and complex compounds.

A. G. Betekhtin, The process of ore formation in hydrothermal veins (p. 279–311, 22 figs.).

The alteration of ore within a vein has a facial character. The colloidal formations are of great importance during the deposition of hydrothermal minerals, and may form under a wide range of temperatures and pressures. The heterogenous character of vein texture is explained by the fact that diffusion was hampered by the colloidal character of the medium. The primary colloform texture of ore disappears during the diagenesis. These conclusions are supported with microphotographs of polished sections. Transitions from gels to crystals are explained as the result of change in concentration of the residual solution. The morphologic features of colloform formations are discussed in the aspect of recrystallization and metamorphism of hydrothermal deposits. The metamorphosed ores exhibit a succession of minerals which does not necessarily correspond to the original succession of the colloform minerals in the vein at the moment of deposition. The process of metamorphism of the primary hydrothermal ores develops under the influence of the changing physico-chemical medium and the concentration of sulfur, oxygen, and carbon dioxide in residual solutions. Ershov (1) suggests that the author should have considered an analysis of typical examples of the transition of soluble compounds into soluble, as the result of alteration of the thermodynamic conditions of the medium.

O. D. Levitskii, The role of colloidal solutions in ore genesis (p. 312–334, 33 figs.).

The author studies the conditions of formation of colloform aggregates of quartz and cassiterite, and their alteration. It is suggested that the different degree of preservation of the colloform textures of both minerals may be explained by the different degrees of stability during the metamorphism. The deposition of ore minerals in the form of gels is a more widespread phenomenon than it is generally accepted, and is not limited to the zone of epithermal deposits. The mineral associations studied by the author belong to the ore bodies formed at different depths. The presence of colloform mineralization should not be considered as an indicator of depletion of an ore deposit with depth.

D. S. Korzhinskii, The outline of metasomatic processes (p. 335–456, 15 figs.).

The endogenous metasomatic processes are analyzed in respect to physical chemistry, relation to magmatic phenomena and to stages of postmagmatic processes. Magmatic processes, metamorphism, and ore formation represent a natural sequence, are frequently superimposed, and are all caused by the ascending magmatogene solutions. The emphasis is placed on metasomatic zoning. The main part of the paper is concerned with a review of contact mineralization such as formation of skarns, contact leaching, and metasomatic rock alteration near the veins. The endogenous metasomatism may be qualified as metamorphism with alteration of the chemical composition. The character of solutions, composition of the country rocks, depth, and the tectonic processes are the principal factors which determine the nature of metasomatic facies. These facies are represented by the solfataric argillization, secondary quartzites, greisenized contacts of granitic intrusions, skarn contacts, propylitization, mica gneisses with muscovite bearing pegmatitization, and different facies of low temperature metasomatism. Ershov (1), discussing the present paper, concludes that the author places emphasis on the development of metasomatism at great depths, where the granitization solutions are active. The problem of genesis of the original magma which yields these solutions, as well as the source of water, which is the main component of these solutions, is not considered. Korzhinskii admits the enrichment of magma with elements derived from the country rock, but does not consider the possible enrichment of hydrothermal solutions.

A. G. Betekhtin, The causes of migration of hydrothermal solutions (p. 456–478, 8 figs.).

Parts of this paper have been published in "Zapiski Vsesoyuznogo Mineralogicheskogo Obshchestva" in 1952. The author makes an approach to the problem in respect to hydrodynamics and hydrogeology. Betekhtin criticizes American geologists for considering the transportation of solutions as mechanical transfer of material without connecting it with the development of accompanying geological processes, such as the formation of fractures. The flow may become effective along the fractures, the formation of which is in progress, if the difference in pressure is created. The mineralizing solutions originate within the intrusions during the cooling of the latter under hypabyssal conditions. The cooling of acid intrusives produces mechanical stresses and formation of hollow contraction fissures with a vacuum. Such fissures and cracks were filled with hydrothermal solutions due to suction. The copper-nickel ores are formed as the result of transfer of the mineralizing solution from the bottom part of the intrusions into the fissures within the underlying rock. Filling of vugs in lava with chalcopyrite and millerite is also caused by suction. The formation of veins of Alpine type is associated with the tension cracks filled with metamorphic solutions due to vacuum. However, O. P. Ogloblina has demonstrated that the crystals may grow

under normal atmospheric conditions, provided the mineralizing solution is supplied through the capillary channels. Betekhtin disagrees with Korzhinskii who says that the growth of crystals is simultaneous with the dissolution of the walls of the fissure. During the formation of ore bodies, the transfer of mineral matter goes on by means of infiltration, and mainly through the diffusion of ions. Ershov (1) says that the process of pulsation has not been taken into account against the background of the evolution of the composition of the ore solutions. There is also no explanation of the cause of succession of elements migrating from the intergranular space into the veins.

A. G. Betekhtin, Genetic relation of hydrothermal deposits with the intrusives (p. 479–520, 1 fig.).

The paper is dedicated to the problem of the source of metallic compounds which accumulate in hydrothermal deposits and to their genetic relation with the intrusive rocks of different types. Besides the associations of metals of particular types of igneous rocks, Betekhtin speaks about the so called "forbidden," anomalous, associations, such as occurrences of tin, gold, lead, zinc, and sometimes tungsten, molybdenum, niobium, thallium, bismuth, arsenic and tellurium, with basic and ultrabasic rocks, platinum with acid intrusives, etc. However, Betekhtin recognizes the possibility of superimposition of hydrothermal deposits derived from different types of magma. The author reviews the hydrothermal deposits which are genetically related with basic and ultrabasic igneous rocks, and acid rocks. The vein deposits are also considered from the point of view of their location in respect of the intrusive bodies, including such deposits which do not exhibit a relation to any intrusive. Speaking of the enrichment of magma with CaO, SiO_2, and Al_2O_3 on account of the country rock, the author does not take into consideration the enrichment of magma with metals from the country rock. Ershov (1) questions this attitude: if the magma can assimilate certain rock-forming compounds, it should also be able to assimilate lead, zinc, molybdenum and other metals. The accentuation by Betekhtin of the role of the unusual "forbidden" associations of metals with intrusive bodies may result in an erroneous direction of exploratory work. The outline of further studies includes the problem of metallogenic provinces and epochs, preparation of metallogenic maps, study of accessory and rare minerals in different types of igneous rocks and the relation of the latter to the minerals of the ore deposits, petrochemical studies of igneous rocks according to Zavaritskii, and study of the isotopic composition of chemical elements in ore minerals. Betekhtin discusses different points of view on the origin of ore solutions and criticizes the theory of "assimilative specialization of magma" by Kh. M. Abdullaev. Abdullaev (2) rejects the critique of Betekhtin and in his turn questions the importance of "forbidden" associations of tin and tungsten with ultrabasic rocks.

F. G. Vol'fson, Structures of endogenetic ore deposits (p. 521–616, 76 figs.).

A review of contributions to the study of structures by M. V. Lomonosov, E. S. Fedorov, V. A. Obruchev, A. E. Fersman, and A. N. Zavaritskii. The structures are discussed in the light of reconstruction of formation of ore deposits, in connection with the evolution of tectonic processes. The structures of ore deposits of different genetic types are illustrated by examples of structures of strictly magmatic deposits, pegmatites, greisens, skarns, and hydrothermal deposits. The classification of structural types is based upon the relation of mineralization to the elements of prototectonic process within the intrusive bodies, form and structure of ore bearing folds, type of ore-bearing fissures, and the direction of movement of blocks during the process of mineralization. Special

attention is paid to the structures of the hydrothermal deposits with reference to the influence of lithology of the country rocks on ore deposition.

This symposium was presented by prominent specialists in the field of ore genesis and contains certain new ideas which would be of interest to the geologists of the western world. Each paper contains references to Russian and foreign sources, including many American. The critique of the western theories makes an impression of unilateralism, such as, e.g., the qualification of Emmons' classification of hydrothermal deposits as idealistic conception, or referring to the American points of view on migration of hydrothermal solutions, as an "example of metaphysical thinking with elements of eclectics." There are almost no changes in the second edition of the book, and therefore excerpts from the critiques by the Russilan geologists of the first edition, remain pertinent to the second edition. One could have expected, as has been suggested by Ershov, that some of the theoretical concepts advocated in this symposium were supported with more experimental data than is the case. It is regrettable that this book is not provided with subject and author index. The first and second editions of the book total 14,000 copies.

REFERENCES

1. Ershov, A. D., 1954, Fundamental problems in study of magmatic ore deposits (discussion): Akademiya Nauk, Izvestiya, Seriya Geologicheskaya, no. 6, p. 111–116.
2. Abdullaev, Kh. M., 1954, Some problems of the genetic relation of hydrothermal formations with the intrusives (discussion): same publication, p. 116–123.
3. Ostrovskii, I. A., 1954, The problem of genesis of hydrothermal deposits (discussion): same publication, p. 123–124.

EUGENE A. ALEXANDROV

DEPARTMENT OF GEOLOGY,
COLUMBIA UNIVERSITY,
July 25, 1958

Einführung in die Gesteinswelt, 2nd Ed. BY HILMAR SCHUMANN. Pp. 189; figs. 52. Steinkopff, Dresden and Leipzig, 1957. Price, DM 9.30.

The title also states that this book is for friends and students of geography, geology, mineralogy, and land forms. Following an introduction on the purposes for which rocks are used and in the development of land forms, the author, who is a professor at Dresden, gives a brief introduction to crystallography. Following this he describes the rock-forming minerals and the rocks composed of them divided into three groups, igneous, sedimentary and metamorphic. The minerals are described briefly and their crystal forms outlined. The rocks of each group are described, their chemical analyses are given, and the mode of occurrence. A final chapter gives the geologic time scale, specific gravity equipment, and tables of minerals and of rocks giving the chief properties and composition. The book should serve the purpose for which it was written.

Subsurface Geology in Petroleum Exploration: A Symposium. Edited by JOHN D. HAUN and L. W. LEROY. Pp. 887. Colorado School of Mines, Golden, Colo., 1958.

This symposium by 48 authors is a compiled outgrowth of Subsurface Geological Methods by L. W. LeRoy, published in 1950. Some of the papers in the predecessor volume have been included with little or no revision. Others have been considerably revised; some have been dropped; and many new ones have been added.

There are eight parts as follows: Introduction; Analysis of Well Cuttings, Cores and Fluids (13 chapters); Well-Logging Methods and Interpretation (9 chaps.); Subsurface Stratigraphy and Structural Interpretation (3 chaps.); Geophysical and Geochemical Prospecting (3 chaps.); Drilling, Formation Testing and Well Completion (10 chaps.); Subsurface Reports (2 chaps.); and Exploration Program (1 chap.) Photos and bibliographies of the 48 authors are given in 24 pages at the end.

The whole range of subsurface petroleum geology and petroleum engineering is covered in the 41 separate chapters. One interesting chapter deals with the procedure and the pros and cons of turbo drilling. Even considerable micropaleontology is included. Numerous illustrations clarify the text.

This volume should prove a handy reference for all interested in subsurface geology and in petroleum engineering.

BOOKS RECEIVED

JAMES M. ALLEN

Gypsum and Anhydrite. A. W. GROVES. Pp. 93. Price, 7 sh. 6 d. Overseas Geological Surveys, London, 1958. *Properties, mode of occurrence, uses of gypsum and anhydrite. World resources.*

Petroleum Sourcebook 1958. CURTIS STEVENS, ED. Pp. 175. National Petroleum Bibliography, Amarillo, Texas, 1958. *An up-to-date regional bibliography of petroleum publications.*

Upper Cretaceous of the Pacific Coast. F. M. ANDERSON. Pp. 359; pls. 75; figs. 3; tbls. 8. Geological Society of America Memoir 71, 1958. *Comprehensive descriptions of stratigraphy, paleontology, structure of the West Coast Cretaceous.*

Petroleum Geology. Vol. 2, No. 2-A. Pp. 54; figs. 12; tbls. 8. Price, $18.00 a year in North America; $20.00 a year outside North America. The Review of Russian Geology, Columbia, South Carolina, 1958. *Six papers translated from the Russian dealing with petroleum geophysics and drilling.*

Minerals Yearbook 1955. Volume I. Metals and Minerals (Except Fuels). STAFF OF THE BUREAU OF MINES. Pp. 1343. Price, $4.25. U. S. Govt. Printing Office, Washington, D. C., 1958. *Statistics of production and use of metals and minerals for the year 1955.*

Minerals Yearbook 1955. Volume III. Area Reports. FIELD STAFF OF THE BUREAU OF MINES. Pp. 1220. Price, $4.00. U. S. Govt. Printing Office, Washington, D. C., 1958. *Statistics of mineral production and use for each state, territory and possession.*

Minerals Yearbook 1956. Volume II. Fuels. STAFF OF THE BUREAU OF MINES. Pp. 449; tbls. 85. Price, $2.50. U. S. Govt. Printing Office, Washington, D. C., 1958. *Statistics of production, use, and economy of the coal and petroleum industries.*

Los Domos Lacoliticos de Tandil. PIERINA PASOTTI. Pp. 71; figs. 30; tbls. 7. Instituto de Fisiografia y Geologia, Rosario, Republica Argentina, 1957. *Description of dome-forming laccoliths found near Buenos Aires. In Spanish.*

The Geology and Mineral Resources of the Lupar and Saribas Valleys, West Sarawak. N. S. HAILE. Pp. 119; pls. 33; figs. 11; tbls. 19. Geological Survey Dept., British Territories in Borneo, Kuching, 1957. *Areal geology of region underlain by sedimentary and igneous rocks of Cretaceous to lower Eocene age. Small occurrences of gold, mercury, manganese, antimony and aluminum are described.*

Carboniferous Stratigraphy and Rugose Coral Faunas of Northeastern British Columbia. P. K. SUTHERLAND. Pp. 175; pls. 33; figs. 4. Price, $2.00. Geological Survey of Canada, Memoir 295, Ottawa, 1958. *Detailed study of rugose coral faunas of the northern Rocky Mountains.*

An Annotated Bibliography on Coal. PARKE O. YINGST. Pp. 77. Price, $1.00. Quarterly of the Colorado School of Mines, Vol. 53, No. 3, Golden, 1958.

Proceedings of the Geological Society of China Number 1 for 1957. Pp. 103; figs. 25. The Geological Society of China, Taipei, 1958. *Several papers dealing with continental drift, continental rifting, various aspects of the geology of Taiwan.*

Annual Report of the Geological Survey Department for the year 1957. F. T. INGHAM. Pp. 39; figs. 6. Price, 100 mils. Cyprus Govt. Printing Office, Nicosia, 1958. *Activities of the geological survey for the year 1957.*

The Egyptian Journal of Geology. Vol. 1, No. 2, 1957. Pp. 153; figs. 26; tbls. 4. Price 50 P.T. The Geological Society of Egypt, Cairo, 1957. *Several papers dealing with granite chronology, petrology, stratigraphy and paleontology. In English or French.*

Geological Survey Annual Report for the Year 1957. Pp. 17; figs. 12. Price, 2 sh. Legislative Council of Fiji, Suva, 1958. *A report of the activities of the Survey during 1957.*

La Chronique des Mines D'Outre-Mer et de la Recherche Minière. Numéro Spécial. Pp. 52; fig. 1. Bureau d'Êtudes Géologiques et Minières, Paris, 1958. *Two papers: bibliographic research into the geology of molybdenum; tectonics of lineaments. In French.*

Bulletin of the Geological Survey of Great Britain. No. 14. Pp. 93; pls. 8; figs. 11. Price, 10 sh. 6 d. Her Majesty's Stationery Office, London, 1958. *Three papers describing regions in England where lead and zinc are mined.*

The Meramec-Chester and Intra-Chester Boundaries and Associated Strata in Indiana. T. G. PERRY and N. M. SMITH. Pp. 107; pls. 6; fig. 1. Price, $2.00. Indiana Geological Survey, Bull. 12, Bloomington, 1958. *Detailed regional study of the Mississippian, Chester, and Meramec formations.*

Petrografia della Serie Solfifera Siciliana e Considerazioni Geologiche Relative. LEO OGNIBEN. Pp. 269; figs. 100. Servizio Geologico d'Italia, Roma, 1957. *Stratigraphy and petrology of the Upper Miocene sulphur series of Sicily. In Italian; English abstract.*

Geološki Glasnik 1956. Bulletin Géologique. Pp. 94; figs. 66. Zavod za Geološka Istraživanja i Ispitivanja Gradevinskih Materijala i Tla N. R. Bih. Sarajevo, 1956. *Several papers on various geological subjects, including petrology, areal geology and ore microscopy. In Jugoslavian; German and English summaries.*

The Water Resources of Antigua and Barbuda B.W.I. P. H. A. MARTIN-KAYE. Pp. 343; pls. 4. St. John's, Leeward Islands, 1956. *Fresh water resources of Antigua and Barbuda.*

Annual Report for 1957. Pp. 8; fig. 1. Price, 1 sh. Water Development and Irrigation Dept., Northern Rhodesia. *A report of ground water studies in Northern Rhodesia during 1957.*

Oklahoma Geology Notes, Vol. 18, Nos. 6 and 7. Pp. 30; pls. 2; figs. 132. Oklahoma Geological Survey, Norman, 1958. *Conodont classification, photographic illustrations of fossil spores from Iowa, and miscellaneous short notes.*

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Observations Relating to Quaternary Environments in East and Southern Africa. H. B. S. Cooke. Pp. 69; pls. 4; figs. 11; tbls. 6. The Geological Society of South Africa, Johannesburg, 1958. *Discussion of the Quaternary geology of southern Africa and how it may have been influenced by climate.*

Boletin de Geologia. Vol. IV, No. 9. Pp. 97; figs. 52; tbls. 4. Republica de Venezuela Ministerio de Minas e Hidrocarburos, Caracas, 1957. *Various papers dealing with: areal geology, petrogenesis, sedimentation. In Spanish.*

Peat Resources of Washington. G. B. Rigg. Pp. 267; pl. 1; figs. 263. Price, $4.00. State of Washington, Division of Mines and Geology, Bull. 44, Olympia, 1958. *Detailed description of peat deposits, location, types of peat and uses.*

Geological Survey of Alabama—University, 1957.

County Rept. 3. Geology and Ground-Water Resources of Madison County, Alabama. G. T. Malmberg and H. T. Downing. Pp. 129; pls. 24; figs. 25; tbls. 11. *Amount, distribution, quality and potential supplies of water.*

Annual Reports for the Fiscal Year October 1, 1955–September 30, 1956. W. B. Jones. Pp. 39; figs. 8. *Annual Report of the Geological Survey of Alabama and the State Oil and Gas Board.*

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No. 11. Boletim do Int. Pp. 50; figs. 23. *Various technical papers including one on the x-ray study of clays. In Portuguese.*

No. 12. Boletim do Int. Pp. 19; fig. 1; tbls. 4. *Three technical papers including one on the evaluation of columbite-tantalite ores. In Portuguese.*

No. 13. Boletim do Int. Pp. 51; figs. 11. *Five technical papers. In Portuguese.*

California Department of Natural Resources, Division of Mines—San Francisco, 1958.

Spec. Rept. 52. Index to Geologic Maps of California to December 31, 1956. Pp. 127. Price, $1.00.

Bull. 175. Salt in California. W. E. Ver Planck. Pp. 165; pls. 2. Price, $3.25. *Geologic occurrence, methods of recovery and treatment, marketing of salt in California.*

Georgia Geological Survey—Atlanta, 1958.

Bull. 67. The Geology of Hart County, Georgia. W. H. Grant. Pp. 75; pls. 5; figs. 30; tbls. 13. *Areal geology of a metamorphic terrain in northeast Georgia.*

Georgia Mineral Newsletter. Vol. XI, No. 1. Pp. 36; figs. 20. *Various papers on mineral and water resources.*

Idaho Bureau of Mines and Geology—Moscow, 1958.

Pamphlet 115. Uranium, Thorium, Columbium, and Rare Earth Deposits in the Salmon Region, Lemhi County, Idaho. A. L. Anderson. Pp. 81; pls. 2; figs. 6. *Detailed description of lode-type uranium deposits, columbium-rare earth deposits of the carbonatite type, and thorite-rare earth veins in shear zones and associated with gold-quartz veins and copper lodes.*

Pamphlet 116. Gold-bearing Gravels near Murray, Idaho. WAKEFIELD DORT, JR. Pp. 21; figs. 5. *Geologic setting, types of gravels, geomorphic history of gold-silver placer deposits. Total production, $6,000,000.*

Illinois Geological Survey—Urbana, 1958.

Rept. of Investigations 206. Studies on Petroleum with the Ultracentrifuge. P. A. WITHERSPOON. Pp. 82; pls. 4; figs. 34; tbls. 27. *Studies with the ultracentrifuge indicate that colloidal particles are present in crude oils.*

Circ. 254. Age of the Springville Shale (Mississippian) of Southern Illinois. CHARLES COLLINSON and A. J. SCOTT. Pp. 12; figs. 6; tbl. 1. *On the basis of this work the Springville is assigned to the Kinderhook rather than the Valmeyer series.*

Groundwater Maps for General Distribution in Illinois. R. E. BERGSTROM and LIDIA F. SELKREGG. Pp. 12; figs. 6. *Description of the way in which ground water data is presented on maps.*

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1958.

Explanatory Text of the Geological Map of Japan. Tappu (Asahikawa-38). K. TSUSHIMA, K. TANAKA, K. MATSUNO and S. YAMAGUCHI. Pp. 74; figs. 11; tbls. 12. *Areal geology of a region in northern Hokkaido underlain by Cretaceous, Tertiary and Quaternary sediments. Coal seams are worked in the area, and placer platinum was recovered at one time. In Japanese; English summary.*

Bulletin of the Geological Survey of Japan, Vol. 9, No. 4. Pp. 90; pls. 6; figs. 52. *Five papers dealing with ground water, clay deposits, and a submarine gravity survey. In Japanese; English abstracts.*

Kansas Geological Survey—Lawrence, 1958.

Bull. 130, Pt. 3. Environment of Deposition of the Grenola Limestone (Lower Permian) in Southern Kansas. N. GARY LANE. Pp. 45; pls. 6; figs. 5; tbls. 9. *Grenola limestone laid down under generally transgressive conditions.*

Preliminary Regional Structural Contour Map on Top of the Stone Corral Formation (Permian) in Kansas. D. F. MERRIAM.

Producing Zones of Kansas Oil and Gas Fields. P. L. HILPMAN. Pp. 10; pls. 2; figs. 2. *Classification of 18 producing zones; geologic and geographic description of each.*

New Zealand Geological Survey—Wellington, 1957.

Bull. n.s. 55. The Geology of Waitaki Subdivision. MAXWELL GAGE. Pp. 132; figs. 33; tbls. 19; maps 4. *Geomorphology, stratigraphy, structure, economic geology.*

Bull. n.s. 56. The Geology of Reefton Subdivision. R. P. SUGGATE. Pp. 144; figs. 36; tbls. 12; maps 10. *Physical geology of coal mining region on the west coast of South Island.*

Ontario Department of Mines—Toronto, 1958.

Sixty-Sixth Annual Rept.—Vol. LXVI, Pt. 4, 1957. Geology of the Werner Lake-Rex Lake Area. H. D. CARLSON. Pp. 29; pls. 4; maps, 4. *Areal geology of a metamorphic-igneous terrain in northwest Ontario. Area noted for the occurrence of nickel-copper-cobalt deposits associated with mafic and ultramafic intrusive bodies.*

Bull. 25. List of Publications (Revised to April, 1958). Pp. 69; figs. 4.

Institute of Mineralogy, Paleontology, and Quaternary Geology, University of Lund—Sweden, 1958.

Publ. 46. Origin of the Manganese Ore Deposit of Bölet, Southern Sweden. PONTUS LJUNGGREN. Pp. 12; figs. 2. *Description of manganese deposit in brecciated granite. Manganite, the chief ore mineral, is thought to have formed from the quadrivalent oxides, under reducing conditions.*

Publ. 47. The Black Beach Sands of Iztapa on the Pacific Coast of Guatemala. PONTUS LJUNGGREN. Pp. 10; fig. 1; tbls. 4. *Black sands consisting of olivine, augite, hypersthene and titaniferous magnetite derived through the weathering of andesite and basalt.*

Virginia Division of Mineral Resources—Charlottesville, 1958.

Bull. 73. Industrial Limestones and Dolomites in Virginia: James River District West of the Blue Ridge. R. S. EDMUNDSON. Pp. 134; pls. 7; fig. 1; tbls. 8. *Results of study made to determine location, thickness and chemical composition of carbonate rocks.*

Bull. 74. Geology and Mineral Resources of the Lynchburg Quadrangle, Virginia. W. R. BROWN. Pp. 97; pls. 14; figs. 6; tbls. 9. *Stratigraphy, petrology, structure, geologic history, and mineral resources of an area straddling the Martic overthrust.*

U. S. Geological Survey—Washington, D. C., 1957–58.

Prof. Paper 301. Exploration of Naval Petroleum Reserve No. 4 and Adjacent Areas Northern Alaska, 1944–53. Pt. 1, History of the Exploration. J. C. REED. Pp. 185; pls. 3; figs. 101. *An account of the search for oil in northern Alaska from 1944 to 1953.*

Prof. Paper 314-B. *Bathygalea*, a Genus of Moderately Deep-Water and Deep-Water Miocene to Recent Cassids. W. P. WOODRING and A. A. OLSSON. Pp. 6; pls. 5; fig. 1.

Bull. 1032-D. Geology of the Copper King Uranium Mine Larimer County Colorado. P. K. SIMS, GEORGE PHAIR, and R. H. MOENCH. Pp. 58; figs. 15; pls. 3; tbls. 5. Price, 75 cents. *Uranium mineralization in pyrometasomatic sulphide magnetite deposits and in veins in a skarn zone.*

Bull. 1042-M. Optical Calcite Deposits in Park and Sweet Grass Counties, Montana. W. C. STOLL and F. C. ARMSTRONG. Pp. 45; pls. 19; figs. 2; tbls. 6. *Optical quality calcite occurs in veins cutting sediments. Total production small; area inactive at present.*

Bull. 1057. Geology of the Manganese Deposits of Cuba. F. S. SIMONS and J. A. STRACZEK. Pp. 283; pls. 32; figs. 50; tbls. 3. *Description of properties, types of deposits, location, geologic setting of deposits. Two main types are recognized—bedrock and surficial. Production since 1888 estimated at 3.5 million tons. High grade reserves estimated at 1,000,000 tons.*

Bull. 1066-E. Index to Geophysical Abstracts 168–171 1957. *Abstracts of world literature contained in periodicals, books and patents.*

Bull. 1072-A. Records of Unsuccessful Test Wells Drilled for Oil and Gas in Mississippi As of July 1, 1956. HELEN M. BEIKMAN, and SOPHIE DRAKOULIS. Pp. 66; figs. 2. Price, 30 cents. *Stratigraphic information on more than 2,200 unsuccessful wells.*

Bull. 1086-A. Geophysical Abstracts 172 January–March 1958. MARY C. RABBITT, DOROTHY B. VITALIANO, S. T. VESSELOWSKY and OTHERS. Pp. 81. Price, 35 cents.

Water-Supply Paper 1307. Compilation of Records of Surface Waters of the United States through September 1950. Pt. 4. St. Lawrence River Basin. J. V. B. WELLS. Pp. 390; pl. 1; figs. 2. *Surface water data from 1835 to 1950.*

Water-Supply Paper 1310. Compilation of Records of Surface Waters of the United States through September 1950. Pt. 6-B. Missouri River Basin below Sioux City, Iowa. J. V. B. WELLS. Pp. 609; pl. 1; figs. 2.

Water-Supply Paper 1370-A. Floods of June 1954 in Iowa. I. D. YOST. Pp. 105; pl. 1; figs. 29; tbls. 7. *Description of floods and flood damage caused by abnormally heavy rains.*

SOCIETY OF ECONOMIC GEOLOGISTS

ANNUAL MEETING

St. Louis, Missouri **November 6–8, 1958**

The 1958 Annual Meeting of the Society of Economic Geologists will be held in conjunction with the Meetings of the G.S.A. and Associated Societies, at St. Louis, Missouri, November 6, 7, and 8. Headquarters will be at the Sheraton-Jefferson Hotel.

The following technical papers will be presented at the time and place indicated:

Friday Afternoon, November 7, Gold Room

Chairmen: Robert Grogan and Charles Meyer

1. 2:00 Paul H. Jones * and V. Subramanyam: Geology and ground-water conditions in the Neyveli lignite area, South Arcot district, Madras State, India.
2. 2:20 H. G. Rodis: Use of water-well data in interpreting the occurrence of Upper Cretaceous aquifers in northeastern Lyon County, Minnesota.
3. 2:40 Chas. H. Behre, Jr.: Origin of ore deposits of the Mississippi Valley type.
4. 3:00 James H. Davis: Distribution of copper, zinc, and minor metals in the Southeast Missouri lead district.
5. 3:20 David L. Kendall: Sedimentary features of the ore deposits, Jefferson City mine, Tennessee.
6. 3:40 George M. Brownell: Beryllium detector for field exploration.
7. 4:00 Siegfried Muessig: Primary borates in playa deposits: minerals of high hydration.
8. 4:15 Eugene N. Cameron and Mary E. Emerson *: Origin of certain chromite deposits of the eastern part of the Bushveld complex.
9. 4:30 R. K. Sorem * and E. N. Cameron: Manganese ores of the Nsuta deposit, Ghana.
10. 4:45 M. P. Nackowski: Physical and chemical environment of Illinois-Kentucky fluorspar deposits.
11. 5:00 Charles B. Sclar * and Mark G. Smerchanski: Columbium-rare earth-titanium mineralization at St. Joseph Du Lac, Oka area, Two Mountains County, Quebec.
12. 5:15 Alfred L. Anderson: Genetic aspects of the monazite and columbium-bearing Rutite deposits in Northern Lemhi County, Idaho.

Saturday Morning, November 8, Gold Room

Chairmen: M. L. Jensen and F. S. Turneaure

1. 8:30 F. Donald Bloss * and Robert L. Steiner: Suggestions on geochemical prospecting for manganese in northeast Tennessee.
2. 8:45 Carl F. Austin * and Mathew P. Nackowski: Geochemical exploration at Darwin Mines, California.

* Indicates speaker.

3. 9:00 W. C. Kelly *, Taro Takahashi, C. H. Behre, Jr., J. J. Durek, G. E. Stoertz, and B. E. Felber, Jr.: Progress in leached outcrop studies.
4. 9:20 Paul B. Barton, Jr., and Philip M. Bethke *: Thermodynamic properties of some synthetic zinc and copper minerals.
5. 9:40 H. L. Barnes: Measurement of the solubility of ZnS in H_2S-saturated H_2O.
6. 10:00 Donald E. White: Liquid of inclusions in sulfides from Tri-State (Mo.-Kans.-Okla.) is probably connate in origin.
7. 10:15 Robert I. Davis: Gold-copper deposits near Santa Maria del Oro, Durango, Mexico.
8. 10:30 F. B. Whiting: Structural belts and mineral deposits of northwestern Argentina.
9. 10:45 Ogden Tweto: Time relations of intrusion, faulting, and mineralization at Leadville, Colorado.

11:00 *Presidential Address* by *George Melvin Schwartz: Hydrothermal alteration.*

Saturday Afternoon, November 8, Boulevard Room

Chairmen: Richard Lund and James Pollock

1. 2:30 Lawrence Y. Marks: Ground-water conditions and the relation to uranium deposits in the Gas Hills area, Fremont and Natrona Counties, Wyoming.
2. 2:45 John W. Gruner: Action of crude oils on uranyl solutions.
3. 3:00 Robert H. Moench: Some clues to the genesis of uranium deposits in the Laguna district, New Mexico.
4. 3:15 Duncan R. Derry: Evidence on the origin of Blind River uranium: a progress report.
5. 3:30 Stafford C. Happ: Some sedimentary characteristics of uranium host rocks.
6. 3:45 Donald S. Miller * and J. Laurence Kulp: Isotopic relations in uranium deposits of the Colorado Plateau.
7. 4:00 A. T. Miesch *, E. M. Shoemaker, W. L. Newman, and W. I. Finch: Chemical composition as a guide to the size of sandstone-type uranium deposits in the Morrison formation on the Colorado Plateau.
8. 4:15 D. Hoye Eargle: Regional structure and lithology in relation to uranium deposits, Karnes County area, Texas.
9. 4:25 Alice D. Weeks *, Betsy Levin, and Robert J. Bowen: Zeolitic alteration of tuffaceous sediments and its relation to uranium deposits in the Karnes County area, Texas.
10. 4:35 J. A. MacKallor * and Carl M. Bunker: Ore controls in the Karnes County uranium area, Texas.
11. 4:45 G. E. Manger: Comparison of the physical properties of uranium-bearing rocks in the Colorado Plateau and the Gulf Coast of Texas.

TO BE READ BY TITLE

1. G. C. Amstutz: Origin of the Mississippi Valley type deposits.
2. E. Wm. Heinrich, A. A. Levenson, J. M. Axelrod, and Charles Milton: Niobium-titanium-rare earth minerals of Ravalli County, Montana, and Lemhi County, Idaho.

* Indicates speaker.

3. Frederick J. Kuellner, John H. Carmen, and Jacques R. Renault: Alkali feldspars from ore and non-ore-bearing parts of some intrusive porphyries.
4. John F. McCauley: Red-bed uranium occurrences in Pennsylvania.
5. James D. Stephens and L. B. Sand: Alteration in part of the United States mine, West Mountain (Bingham) district, Utah.
6. Alice D. Weeks and Alfred H. Truesdell: Mineralogy and geochemistry of the uranium deposits of the Grants district, New Mexico.

Immediately after the Presidential Address there will be a social get-together in the Gold Room extension. A bar will be available.

The Annual Luncheon will be served in the Gold Room at 12:30 P.M. This will be followed by a brief business meeting, President Schwartz presiding. Tickets for the luncheon are $3.50 each. They should be purchased in advance, either through the GSA Advance Registration or at the GSA Registration Desk.

Non-members of the Society are welcome to attend any or all of the functions.

HAROLD M. BANNERMAN
Secretary

ABSTRACTS OF PAPERS TO BE
READ BEFORE THE MEETING OF THE SOCIETY,
ST. LOUIS, MISSOURI, NOV. 6–8, 1958

GENETIC ASPECTS OF THE MONAZITE AND COLUMBIUM-BEARING RUTILE DEPOSITS IN NORTHERN LEMHI COUNTY, IDAHO

ALFRED L. ANDERSON
Department of Geology, Cornell University, Ithaca, New York

Deposits of monazite and columbium-bearing rutile in a belt more than 10 miles long in northern Lemhi County, Idaho, are distinguished by their notable concentrations of rare earth elements, thorium, titanium, columbium, iron, calcium, barium, phosphorus, sulfur, and silica, and particularly by their abundance of carbonates, chiefly ferriferous calcite. These deposits occur as structurally controlled replacements of crystalline limestones, amphibolites, and porphyroblastic gneisses which form a part of the complex metamorphic border zone of the Idaho batholith. The deposits are mostly small, tabular, and show a sporadic and irregular distribution of minerals, the most abundant of which are actinolite, allanite, monazite, apatite, barite, columbium-bearing rutile, ilmenite, magnetite, and calcite. Minor minerals, some of them sparse, include biotite, garnet, glaucophane, sphene, pyrite, pyrrhotite, and chalcopyrite. The silicates were deposited first, then successively phosphates, sulfates, oxides, carbonates, and sulfides. Most of the thorium entered the allanite rather than the somewhat later monazite.

The deposits possess all the compositional characteristics of the carbonatites, but differ from the type carbonatites in their apparent lack of association with alkalic igneous rocks. They appear to have been made by hydrothermal solutions genetically related to the Idaho batholith.

GEOCHEMICAL EXPLORATION AT DARWIN MINES, CALIFORNIA

CARL F. AUSTIN AND MATHEW P. NACKOWSKI
Department of Mining and Geological Engineering, University of Utah, Salt Lake City, Utah

Geochemical samples were collected from five localities in silicated limestones at the lead-zinc-silver replacement type ore deposits at Darwin Mines, Darwin,

California. The localities sampled included fractures and contacts between silicated limestone and replacement type ores, diorite, and feldspathic limestone.

Samples were analyzed spectrochemically. Preliminary semi-quantitative analyses included lead, silver, zinc, copper, iron, boron, and sodium. Lead was selected as the indicator element for ore. Lead was analyzed quantitatively using bismuth as an internal standard. The precision of the analytical procedure, stated as the relative standard deviation, was $\pm 22\%$.

The following conclusions were reached. The primary trace lead background value in silicated limestones was 18 ppm. Anomalous trace lead values increased logarithmically as ore bodies and mineralizing channels were approached. The dispersion distance in massive wall rock was 8 to 20 feet. Anomalies in trended trace lead dispersion curves reflected the presence of ore bodies. Trended anomalies were found 30 to 60 feet from known ore. Most of the anomalous trace lead was caused by galena, or lead bearing products of weathering. Background values are probably caused by substitution of lead for calcium and potassium in existing minerals or adsorption on mineral surfaces. The dispersion curves indicated either rapid diffusion from a short lived source or slow diffusion from a long lived source. The trace lead dispersion patterns suggested that permeable beds and fractures served as ore solution conduits. Secondary trace lead anomalies were found in chemically weathered areas beneath ore bodies.

MEASUREMENT OF THE SOLUBILITY OF ZnS IN H_2S-SATURATED H_2O

H. L. BARNES

Geophysical Laboratory, Carnegie Institution of Washington, Washington, D. C.

Apparatus and experimental technique have been developed for measuring solubilities up to 400° C and 5,000 psi. By using double valves to withdraw 5 ml samples from a 1 L. reaction vessel, there is a pressure drop of less than 0.5% at approximately constant temperature during the extraction. Corrosion is held to a minimum with thick chrome plating on type 310 stainless steel. The pressure guage is chemically isolated from the system with a "U"-tube containing paraffin oil. Equilibrium is attained in minutes above 50° C by rocking the reaction vessel for agitation. Weighed amounts of solids, liquids, and a gas may be inserted into the reaction vessel without contamination.

In the system ZnS-H_2S-H_2O, polarographically measured solubilities of ZnS exceed 10 mg/L. at 75° C and 300 psi which is more than 10^6 times the calculated solubility product under these conditions. At 25° C and 100 psi, the solubility is not detectable (< 1 mg/L.). The solubility is controlled by the formation of complex ions of the type ($ZnS \cdot H_2S$). The magnitude of the determined solubilities indicates that these complex ions are stable even at low temperatures and pressures. This type of complex is probably not the ore transporting mechanism but a fundamental understanding of this 3-component system is necessary before the 4-component systems containing polysulfide and thiosulfate complexes at high pressures and temperatures can be interpreted.

THERMODYNAMIC PROPERTIES OF SOME SYNTHETIC ZINC AND COPPER MINERALS

PAUL B. BARTON, JR., AND PHILIP M. BETHKE

U. S. Geological Survey, Wash. 25, D. C., and Missouri School of Mines and Metallurgy, Rolla, Mo.

Measurement of pH of a solution of known Zn^{+2} or Cu^{+2} concentration in equilibrium with the metal hydroxide or oxide allows the calculation of an apparent

equilibrium constant ($K' = [M^{+2}] \cdot a^2_{OH^-}$) which varies with composition of the solution. Extrapolation of K′ values to infinite dilution permits evaluation of a true equilibrium constant ($K = a_{M^{+2}} \cdot a^2_{OH^-}$). This procedure is applied to the determination of the equilibrium constant for ZnO (zincite). $CuCl_2$ and $CuSO_4$ solutions precipitate the basic salts $Cu_4(OH)_6Cl_2$ (atacamite), and $Cu_4(OH)_6(SO_4)$ (brochantite) at concentrations greater than about 10^{-4} molar. Extrapolation to infinite dilution gives the equilibrium constants for these basic salts. At higher pH values reactions such as

$$Cu_4(OH)_6Cl_2 + 2OH^- \quad 4CuO + 2Cl^- + 4H_2O \qquad (1)$$

and

$$Cu_4(OH)_6SO_4 + 2OH^- \quad 4CuO + SO_4^= + 4H_2O \qquad (2)$$

take place and permit the evaluation of K for CuO (tenorite). The variation of K with temperature (25° to 75° C) permits the calculation of heat content for the various precipitates. The data so far obtained are:

	K	$\Delta F°_{298}$ (Kcal/mole)	$\Delta H°_{298}$ (Kcal/mole)
Zincite	$10^{-17.04} \pm 0.1$	−76.9	
Tenorite	$10^{-15.9} \pm 0.2$	−30.1	−38.8
Atacamite	$10^{-49.5} \pm 0.4$	−320.9	−389.9
Brochantite	$10^{-61.6} \pm 0.4$	−434.5	−519.6

To the extent that the pH measurements represent the hydrogen ion activity the ratio K/K′ gives the activity coefficient of the metal ion at any particular ionic strength. The activity coefficients of Cl^- and $SO_4^=$ are derived from $[Cl^-]/a^2_{OH^-} = K_1'$ and $[SO_4^=]/a^2_{OH^-} = K_2'$ obtained by pH measurement from reactions (1) and (2).

The variation of activity coefficient with composition provides an effective means of studying complex formation.

ORIGIN OF ORE DEPOSITS OF THE MISSISSIPPI VALLEY TYPE

CHAS. H. BEHRE, JR.

Department of Geology, Columbia University, New York 27, New York

This much discussed question, to which Allen V. Heyl has contributed valuable comments, is receiving renewed attention here and abroad. Characteristically these deposits bear lead, zinc, and iron sulphides, fluorite, barite, and rarer minerals; accompany silicification, dolomitization, and solution effects; form replacements, disseminations, and fillings of breccia, bedding, and transcurrent fractures in carbonate rocks; lack clearly associated igneous rocks. They include the several Mississippi Valley deposits (in Tennessee, Virginia, and Pennsylvania), probably Metaline, and Pine Point, Canada. Abroad such districts include Derbyshire, northern England, Moresnet-Altenberg (Belgium-Germany), Silesia (Poland), Santander (Spain), the Alps (e.g., Hezica, Bleiberg and Cave del Predil), probably Sardinia, and most lead-zinc deposits in Tunis, Algeria, and Morocco—an incomplete but striking list, economically very important.

Genetic explanations are divided between hydrothermal, supergene, lateral secretion, syngenetic (sedimentary), regeneration, and diagenetic theories. The latter two receive little attention in America but much in Germany.

Regeneration and hydrothermal concepts, essentially identical, avoid the problem of transporting in solution the dissimilar ions concerned and fit inclusion-temperature evidence. Widespread distribution in specific beds is explicable since

occurrences transgress bedding. Analyses by Barnes show that primary (sedimentary) lead and zinc in the most favorable rocks are insufficient to furnish the deposits by lateral secretion or diagenetic mobilization alone. Zoning and alteration as in "hydrothermal" deposits are recognizable. Detailed structural and stratigraphic distribution argue against other than epigenetic origin. Deposition by warm, ascending waters is most favored.

SUGGESTIONS ON GEOCHEMICAL PROSPECTING FOR MANGANESE IN NORTHEAST TENNESSEE

F. DONALD BLOSS AND ROBERT L. STEINER

Department of Geology, Southern Illinois University, Carbondale, Illinois, and Department of Geology and Geography, University of Tennessee, Knoxville, Tennessee

Samples of mature leaves and of second year twigs were collected from 36 chestnut oaks (Quercus prinus) growing above two areas of subsurface manganese mineralization in northeast Tennessee. Of the metals determined to be most abundant in ore specimens and concentrates from the general area (i.e. manganese, iron, barium, cobalt, and nickel in decreasing order of abundance), all but cobalt were readily determinable spectrochemically in the ashed leaves and twigs. The average values (weight per cent) for the tree samples collected, as well as for soil specimens from the one foot depth at each tree locale, were:

	Mn	Ba	Fe	Ni
Twig ash	3.8	1.01	0.24	0.017
Leaf ash	3.8	0.36	0.35	0.014
Near-by-soil	0.29	0.04	6.9	0.001

Of the two areas sampled, one, the Hutchens property, was later developed into an economic ore body whereas the manganese bodies of the Rominger property proved to be too low in over-all concentration to be economic. Significantly, the manganese, barium, and nickel contents of samples from the Hutchens area more frequently exceeded the average values of the preceding table than did those from the Rominger area. Although it was not detectable in the surface soil, the appearance of nickel in excess of average in chestnut oak leaf and twig ash was confined almost exclusively to the Hutchens area, particularly to the trees most closely overlying the subsurface manganese ore body. Nickel in chestnut oak leaf and twig ash seemed likely to be a fairly reliable guide to ore.

A BERYLLIUM DETECTOR FOR FIELD EXPLORATION

GEORGE M. BROWNELL

The portable instrument, here referred to as a "berylometer," is a new geophysical tool for the use of the geologist in both exploration and examination of beryllium deposits. This is a scintillation counter which contains a phosphor having a high neutron to gamma ratio of detection and makes use of the Be^{9} $(\gamma, n)Be^{10}$ reaction. A gamma emitting source is carried in a shield on the bottom of the instrument which, when set upon any beryllium-bearing mineral or rock, causes the emission of neutrons from the beryllium which are immediately recognizable. Gamma rays are biased out and neutrons only are counted. An automatic counting register records the neutron count and since this is directly pro-

portional to the beryllium content of a sample, a simple means of analysis is provided.

There is an urgent demand for larger supplies of beryllium and the writer believes that more effort should be directed towards discovering non-pegmatitic deposits that offer greater possibilities of large tonnage. The discovery of such deposits should be greatly facilitated by use of the berylometer.

THE ORIGIN OF CERTAIN CHROMITE DEPOSITS OF THE EASTERN PART OF THE BUSHVELD COMPLEX

EUGENE N. CAMERON AND MARK E. EMERSON *

Department of Geology, University of Wisconsin, Madison, Wisconsin

The Steelpoort and Leader chromitite seams are enclosed in feldspathic pyroxenites of the lower part of the Critical Zone in the eastern part of the Bushveld Complex. The Steelpoort seam consists of 44 to 48 inches of high-grade chromitite enclosed in two low-grade members that are transitional into the enclosing pyroxenites. The Leader seam, 4 feet above the Steelpoort seam, consists of 12 inches of high-grade chromitite overlain by 2 inches of low-grade chromitite transitional upward into pyroxenite.

Textures of the pyroxenites and low-grade chromitite members are consistent with differential settling of bronzite and chromite crystals from moving magma, followed by crystallisation of interstitial liquid. Textures of the high-grade chromitite members, however, indicate that in these members settling of chromite crystals was followed by formation of additional chromite in situ.

Bronzite and chromite vary systematically in grain size and composition through the pyroxenite-chromitite sequence. From this and from textural evidence, we suggest that formation of the high-grade chromitite members involved partial resolution and reaction of settled crystals with magma prior to burial, followed by reaction between settled crystals and interstitial liquid after burial. Downward diffusion of ions into the interstitial liquid during crystallisation may have contributed to growth of chromite.

Formation of the chromitites from residual liquids rich in Cr and Fe is excluded by field evidence and by the paragenetic sequences of minerals in associated rocks. Liquid immiscibility, if operable, played only a minor role in chromitite formation.

DISTRIBUTION OF COPPER, ZINC AND MINOR METALS IN THE SOUTHEAST MISSOURI LEAD DISTRICT

JAMES H. DAVIS (INTRODUCED BY JOHN S. BROWN)

35 "D" Street, Bonne Terre, Missouri

Study of the distribution of the various metals relative to one another and to structural features contributes to the understanding of the Southeast Missouri lead-zinc ores.

Within the central part of the district, occurrences of appreciable sphalerite and chalcopyrite are mutually exclusive. Copper mineralization is concentrated in the eastern part of the district and appears to be related to a particular fault system. Zinc occurs mostly in the central part of the area and fault correlation is less obvious. Some deviations from this pattern are noted.

Most occurrences of conspicuous siegenite are in the same general areas as the copper mineralization. Nickel also occurs as nickeliferous pyrite (bravoite). Trace amounts of zinc, copper, cobalt and nickel are present in most of the ores.

* Speaker.

Cadmium occurs in the lattice of sphalerite. A study of Zn-Cd ratios shows significant variations among several mineralized areas.

Silver occurs in both galena and sphalerite, but is about 20 times as abundant in sphalerite. No silver minerals were identified.

Spectrographic analyses of concentrates from three mills indicates the presence of certain other metals.

Polished surfaces showed the general paragenetic sequence to be (from earliest to latest) marcasite, sphalerite, siegenite, galena, chalcopyrite.

GOLD-COPPER DEPOSITS NEAR SANTA MARÍA DEL ORO, DURANGO, MEXICO

ROBERT I. DAVIS

Apartado 251, Monterrey, N. L., Mexico

The orebodies of the Santa María del Oro gold-copper district occur along a series of prominent northwest-striking fissure veins that cut a fine-grained granite stock. The major veins of the district have been developed over a strike length of nearly three kilometers and to a depth of about 250 meters.

The granite, probably late Mesozoic in age, was intruded at a relatively high crustal level and it arched the cover of interbedded phyllites, quartzites, and basic flows that are believed to be of upper Paleozoic age. Northeast-southwest compression and slightly later north-south compression produced five sets of fractures that served as channelways first for the intrusion of felsite porphyry and diabase dikes, and then for the ascent of the ore solutions.

Two distinct stages of hypogene mineralization are recognized from a study of the vein pattern and a microscopic examination of the altered wall rock and the vein minerals. During the initial stage abundant quartz and pyrite, with lesser amounts of sericite and arsenopyrite filled the fissures; the wall rock was converted to a cryptocrystalline intergrowth of quartz and sericite. Following a reopening of the vein fissures and the formation of some new fractures, specularite, pyrrhotite, chlorite and rhombohedral carbonate were first deposited in both the veins and the wall rock; sulfides and sulfo-salts of copper, lead, and zinc, and abundant carbonate were next precipitated as vein minerals. One of the last minerals deposited was native gold.

EVIDENCE ON THE ORIGIN OF BLIND RIVER URANIUM—PROGRESS REPORT

DUNCAN R. DERRY

Toronto, Canada

With eleven mines in the Blind River area now in full or partial production, evidence on the origin of the uranium mineralization is beginning to accumulate and some provisional conclusions can be drawn.

The facts we have at present are:

(1) Commercial ore is mainly restricted to quartz pebble conglomerate beds included in predominantly quartzitic Lower Huronian sediments and there is a direct relationship between maximum conglomerate development (probably deposited in river estuaries) and grade of uranium ore.
(2) The source of material in the beds is from the northwest.
(3) The proportion of uraninite to brannerite tends to be higher on the south relative to the north side of the main basin.

(4) Age determinations by the Department of Geophysics, University of Toronto, show that definite detrital minerals (zircon and monazite) have an age of about 2500 m.y., while the uraninite and brannerite date at about 1700 m.y. A granite intruding the Mississagi dates at about 1500 m.y.

Conclusions:

(a) The Lower Mississagi (Lower Huronian) was deposited at least 1700 m.y. ago in estuaries of rivers deriving material from an older land mass to the northwest.

(b) Uraninite and brannerite were deposited contemporaneously with, or shortly after, deposition of beds but not as derital material.

(c) Possibility of uranium being deposited from hydrothermal solutions rather unlikely by reason of close association of mineralization with drainage pattern and fact of the only granite intruding Huronian being still younger than the uranium minerals. It seems more likely that the uranium was precipitated in the quartz pebble beds before burial, possibly through the agency of organic material.

REGIONAL STRUCTURE AND LITHOLOGY IN RELATION TO URANIUM DEPOSITS, KARNES COUNTY AREA, TEXAS

D. HOYE EARGLE

U. S. Geological Survey, Austin, Texas

The uranium deposits of the Karnes County area, south-central Texas, are chiefly in tuffaceous sandstones and siltstones of the Jackson formation (late Eocene). In other localities to the northeast and to the southwest uranium has been found in the Catahoula tuff (Miocene?), the Oakville sandstone (Miocene), and in the Goliad sand (Pliocene).

The principal uranium region is broken by two major and several minor faults trending northeast, paralleling the regional strike, and by numerous minor faults that trend north or northwest. The northeast trending faults have impeded the flow of fluids, altering the normal movement of ground water down the dip and providing traps for oil and gas. The two major faults are the Falls City fault in the northeast part of the area, downthrown side to the southeast, and the Fashing fault, southwest of the Falls City fault and roughly en echelon to it, downthrown side to the northwest. The largest uranium deposits discovered to date in the Karnes County area lie in a gently-dipping, warped block several miles wide between the ends of the major faults. The oil fields, with one exception, produce oil or gas from Tertiary units. The Fashing Edwards field produces a gas rich in distillate and sulfur. It may be that slow seepage of gas upward along the faults of the area furnished a precipitant for the uranium concentrated in the ground waters of the area, in the region where the fluid movement has been hindered by the structural anomalies and permeability barriers.

THE ACTION OF CRUDE OILS ON URANYL SOLUTIONS

JOHN W. GRUNER

University of Minnesota, Dept. of Geology & Mineralogy, Minneapolis

The discovery in 1955 of very large uranium deposits in the San Juan Basin north of Grants, New Mexico, shows that organic matter in the form of dried "dead" oil which surrounds the sand grains was instrumental in precipitating vast amounts of reduced uranium compounds.

A number of experiments with crude oils and "dried" crude oils show conclusively that uranium is easily precipitated at 120–125° C as uraninite if the pH

of the aqueous solution in contact with the oil is below 8. When Ca-uranyl tricarbonate is reduced under these conditions, uraninite and calcite form a result similar to some natural occurrences. The temperature of 120–125° C was used to speed up the reaction which otherwise might have taken years. What constituents of the oils are most effective is not known at present but H_2S could not be detected in the oils. Saturated hydrocarbons alone do not seem to reduce uranyl ions.

SOME SEDIMENTARY CHARACTERISTICS OF URANIUM HOST ROCKS

STAFFORD C. HAPP

456 Elm Court, Grand Junction, Colorado

Over 90 percent of known uranium ore in western United States is at relatively shallow depths in rocks formed from stream channel sediments. Evaluation of additional potential reserves involves both sources of mineralizing solutions, yet little known, and distribution of favorable lithology in large areas where potential host rocks are deeply buried, or little explored.

Sudden abandonment of channel segments by avulsion preserves sands and gravels in their normal stream channel pattern, (1) lag deposits below, (2) overlying transitory bedload, and (3) crescentic lateral accretion or point bar deposits interfingering with overbank sediments on convex banks. Such abandoned channels are most likely where confined between cohesive banks, as in the claystone-mudstone sequences of the Brushy Basin member of the Jurassic Morrison formation, or the Triassic Chinle formation above its basal sandstones.

Freely meandering streams form extensive sand deposits with inconspicuous individual channel patterns, but broader, less sinuous, elongate meander belts. Such may be extensive sandstones in the Salt Wash member of the Morrison.

Extensive deposits such as the Shinarump member of the Chinle, filling elongate depressions in older bedrock, probably represent filled valleys rather than individual streams. Anastomosing Shinarump "channels" suggest diversions across cols between aggraded valleys.

Streams usually erode into bedrock only in localized scours, chiefly at bends during high stages. Thus irregular longitudinal bedrock profiles are expected; but stream bend migration may greatly distort individual crescentic scours.

GEOLOGY AND GROUND-WATER CONDITIONS IN THE NEYVELI LIGNITE AREA, SOUTH ARCOT DISTRICT, MADRAS STATE, INDIA

PAUL H. JONES [1] AND V. SUBRAMANYAM [2]

U. S. Geological Survey, Memphis General Depot, U. S. Army, Memphis, Tennessee

Unconsolidated deposits of the Cuddalore series of Miocene age underlie much of the coastal plain of southern Madras. Several lignite seams occur in a thick sequence of sand, gravel, and clay that dips seaward about 40 to 100 feet per mile. The principal seam of lignite mapped in the Neyveli area average more than 50 feet in thickness, underlies at least 80 square miles, and occurs at a minimum depth of 165 feet near Neyveli, where deposits totalling 230 million tons have been proved in an area of 4½ square miles.

The lignite seam is immediately underlain, throughout its area of occurrence, by a thick bed of sand and gravel that contains artesian water, the head of which

[1] Geologist, U. S. Geological Survey, Memphis, Tennessee.
[2] Geologist, Geological Survey of India, Calcutta.

is more than 100 feet above the top of the lignite at Neyveli. The sand and gravel aquifer is exposed to recharge in and near its outcrop area, 6 to 10 miles northwest of Neyveli, where the average annual rainfall is 41 inches.

Hydraulic tests of the aquifer indicate that ground-water control for mining by opencast from a pit 6000 feet long and 1200 feet wide will require continuous withdrawal of about 40,000 gallons (Imperial) per minute from wells in and adjacent to the mine. The well field, including 50 to 65 large-capacity wells, must move with the open cut; and no appreciable decrease in the withdrawal rate can be expected throughout the life of the mine, which is designed to produce about 3½ million tons of raw lignite per year.

PROGRESS IN LEACHED OUTCROP STUDIES

W. C. KELLY, TARO TAKAHASHI, C. H. BEHRE, JR., J. J. DUREK, G. E. STOERTZ, AND B. E. FELBER, JR.

Dept. of Geology, University of Michigan, Ann Arbor, Michigan, and Dept. of Geology, Columbia University, New York 27, New York

Studies by Locke, Blanchard, and associates on copper, lead and zinc gossans suggest supplementing their methods with modern geochemical and mineralogical techniques to aid difficult search for ore. Work, begun in 1954 on lead and zinc, was later extended to copper. Field and laboratory studies were helped by the New Mexico Bureau of Mines; mining companies (American Metal, American Zinc, Anaconda, Kennecott, Peru, U.S.S.R., and M., and Universal Exploration); and the U. S. Geological Survey Staff at Platteville.

Results, generalized:

1. Mobility and distribution of oxidation products were re-confirmed in new districts.
2. The commonest zinc oxidation products respond to pH of groundwater and climate: at Goodsprings, Nev. (pH 8–9, rainfall 4 inches) hydrozincite preponderates; at Platteville, Wis. (pH 7–7.5, rainfall 35 inches), smithsonite; in eastern Tennessee (pH 4–5, rainfall 44 inches), hemimorphite.
3. In oxidized lead ores, Mo and As (e.g., wulfenite and mimetite) originate from sulfides; Va and P (e.g., vanadinite and pyromorphite), from carbonate rocks.
4. "Boxworks" as clues require extreme caution: such textures also result from fracturing.
5. Color is useful locally only after the range typical for a known ore is locally established.
6. Porosity suggests the amount of soluble primary ions (e.g., Cu, Zn) in the sulfide ore, subsequently removed. However, allowance must be made for: (a) primary ore porosity; (b) cavity filling by transported limonite; (c) leaching of gangue or rock.
7. Goethite being virtually the only form of "limonite" commonly developed, its relation to lepidocrocite is useless as quide to primary ore composition.

SEDIMENTARY FEATURES OF THE ORE DEPOSITS, JEFFERSON CITY MINE, TENNESSEE

DAVID L. KENDALL

The New Jersey Zinc Company, Jefferson City, Tennessee

The Mascot-Jefferson City zinc district, extending from about 15 to 30 miles northeast of Knoxville, lies in central East Tennessee, in the Appalachian Valley and Ridge province. The ore bodies, confined to dolomitized limestone in the lower Ordovician Kingsport and Longview formations are elongated and continuous with bedding but are irregular in detail. Distinction is made between

coarse-grained and fine-grained dolomites. Both types are believed to have been formed penecontemporaneous with deposition. Sedimentary breccias of two principle types are distinguished: coarse-grained dolomite breccias located in dolomitized limestone beds and restricted to these beds; and, fine-grained dolomite breccias, cross-cutting the stratigraphic section. Ore has replaced the coarse-grained breccias but the fine-grained breccias are barren. Non-sedimentary crackle or mosaic breccias in fine-grained dolomite have localized ore as fracture fillings. Bleaching of fine-grained dolomite beds is spatially related to ore deposits. Vug-filling laminated clastic dolomite with laminations apparently parallel to country rock bedding is post-ore and suggests ore deposition while beds were flat. The marked stratigraphic restriction of the ore and its intimate relation with sedimentary structures, together with the lack of features customarily cited as criteria of hydrothermal deposition require an unorthodox theory of origin. Concentration and deposition from the sea penecontemporaneous with sedimentation is suggested. Later regeneration of such a deposit would explain the migration of mineralization into fractured fine-grained dolomite.

ORE CONTROLS IN THE KARNES COUNTY URANIUM AREA, TEXAS

J. A. MACKALLOR * AND CARL M. BUNKER

U. S. Geological Survey, Washington, D. C., and Denver, Colorado

The principal ore host rock in the Karnes County uranium area is the Stones Switch sandstone member (Ellisor, 1933) of the Jackson formation (late Eocene). Most commonly the Stones Switch consists predominantly of sand, grading into silt at the base. In western Karnes County, however, the lithologic sequence changes significantly. Most of the important ore bodies are several hundred feet up dip from a mudstone-filled "channel" cut deeply into or through the Stones Switch. The channel roughly parallels the north to northeast strike of the Stones Switch, is from 200 to 400 feet wide, and is about 25 feet deep.

Adjacent and parallel to the mudstone channel the Stones Switch consists of a sequence of alternating sands, silts and mudstones in contrast to the sand that predominates elsewhere. The most important deposits are in the sequence of varied lithology of lower permeability rather than in the more permeable sandy facies.

In one locality gamma-ray logs show a radioactive zone along the bedding, extending down dip from a small ore deposit to the mudstone channel where the radioactive zone ends abruptly.

The mudstone channel and changes in lithology and permeability seem to have influenced the deposition of ore, evidently through control of ground-water movement in a suitable reducing environment.

A COMPARISON OF THE PHYSICAL PROPERTIES OF URANIUM-BEARING ROCKS IN THE COLORADO PLATEAU AND THE GULF COAST OF TEXAS

G. E. MANGER

U. S. Geological Survey, Washington, D. C.

Physical properties of cores obtained by drilling with oil-base mud to depths of 300 feet in a uranium area in the Gulf Coast of Texas are similar in part to properties of cores from similar depths in several uranium areas in the Colorado Plateau.

* Speaker

The ore, whether oxidized or unoxidized, is below but near the top of a relatively saturated sandstone unit, or water zone, which is overlain by a relatively dryer or desaturated zone. In the permeable desaturated and water zones in the Gulf Coast area, 65 and 94 percent, respectively, of the pore space is occupied by formation water; in the Colorado Plateau areas these zones contain 6 and 30 percent pore water, respectively. These zones are probably below a perched water table in the Colorado Plateau areas and probably below the regional water table in the Gulf Coast area.

The ore in all areas represents concentrations of uranium in one to three feet of sandstone of variable permeability lying within a thicker and relatively permeable sandstone body. Water leaches of the cores yield soluble material greatly exceeding that in the formation water and show minimum pH in and near the ore. The Gulf Coast samples show increased chlorinity with increased concentrations of uranium. Concentrations of carbonaceous material occur with and outside of concentrations of uranium.

GROUND WATER CONDITIONS AND THE RELATION TO URANIUM DEPOSITS IN THE GAS HILLS AREA, FREMONT AND NATRONA COUNTIES, WYOMING

LAWRENCE Y. MARKS

321 North Broadway, Riverton, Wyoming

As ground water apparently leaches, transports, and deposits uranium in the Gas Hills area, central Wyoming, it is important to understand its distribution, movement, and relation to geology and ore bodies. Water table maps were prepared of the Wind River Basin; the most detailed work was in the Gas Hills area.

The water table in the Gas Hills area slopes generally to the northwest, ranges in depth from near the ground surface to more than 200 feet, and has seasonal fluctuation of about 5 feet. Perched water tables and artesian conditions occur locally.

The oxidized-unoxidized rock contact is probably roughly parallel to the water table and averages about 25 feet above it although locally the two surfaces are considerably farther apart and the oxidized-unoxidized contact may be below the water table. In many places the gradient of the water table changes near the contact between rocks of different permeability. It is conformable with the structure at some anticlines and its gradient changes abruptly near some faults.

Most above-normal concentrations of uranium occur at local water table depressions or at water table terraces where the gradient of the water table flattens. At these places, the uraniferous ground water is slowed and is in contact with reducing agents in the rocks for a relatively long time. This may allow reduction of soluble transported uranium (U^{+6}) to insoluble ($U + 4$) so that uranium is precipitated.

CHEMICAL COMPOSITION AS A GUIDE TO THE SIZE OF SANDSTONE-TYPE URANIUM DEPOSITS IN THE MORRISON FORMATION ON THE COLORADO PLATEAU

A. T. MIESCH, E. M. SHOEMAKER, W. L. NEWMAN, AND W. I. FINCH

U. S. Geological Survey, Denver, Colorado

The concentrations of uranium, yttrium, sodium, iron, zirconium, manganese, calcium, and nickel in 75 mill-pulp samples of uranium deposits in the Salt Wash member of the Morrison formation on the Colorado Plateau are related to the sizes

of the deposits represented by the samples. The observed relations may be used to estimate sizes of uranium deposits in the Salt Wash member within broad limits. Three methods of size estimation have been devised. One is based on simple linear regression theory and two are based on multiple regression theory.

Estimates of size based on the methods have, at best, a range of error equal to $Y/45$ to $Y \times 45$ at 95 percent confidence, where $Y =$ size estimate in tons. For 80 percent confidence the error factor can be as low as 12, rather than 45. A group of 40 deposits of known size was used to test the theoretical accuracy of the methods. It was concluded from the test that the theoretical ranges of error describe the accuracy and the precision of the methods satisfactorily.

The methods of size estimation will be useful in predicting sizes of deposits where exposures of the ore are limited or where an independent estimate of size is desired. The error of the methods may be quite large, as is indicated by the confidence limits given above, but they may at least distinguish small deposits with high confidence.

ISOTOPIC RELATIONS IN URANIUM DEPOSITS OF THE COLORADO PLATEAU

DONALD S. MILLER AND J. LAURENCE KULP

Lamont Geological Observatory (Columbia University), Palisades, New York

Uranium, lead and lead isotope measurements have been made on a new collection of pitchblendes, urano-organic minerals and pyrite from each of the major types of uranium mineralization on the Colorado Plateau, i.e., Lisbon Valley, Temple Mountain, Cameron, Grants and Marysvale. A new hypothesis is presented which requires a local source with U/Th and U/Pb ratios, suitable ground water movement, and deposition at the site of H_2S production. Sulfur isotopic data on associated sulfides from these deposits as first shown by Jensen established a low temperature (25–70° C), biogenic origin for the sulfide and hence the uranium deposition. The lead isotopic relations indicate that in some cases the primary ore deposition may have occurred within the last 5 million years, although uranium may have been deposited at different places at other distinct times since the Jurassic. The uranium-lead isotopic ages derived from these materials are "apparent ages" only and bear no direct relation to the time of deposition. The hypothesis of hydrothermal deposition of uranium accompanied by old radiogenic lead from the basement, at one time about sixty million years ago, does not satisfy the isotopic data.

SOME CLUES TO THE GENESIS OF URANIUM DEPOSITS IN THE LAGUNA DISTRICT, NEW MEXICO

ROBERT H. MOENCH

U. S. Geological Survey, Denver, Colorado

The uranium deposits of the Laguna district, New Mexico, include large semitabular and smaller pipelike deposits in the Jackpile sandstone (of local usage) in the Morrison formation, small semitabular deposits in the Entrada sandstone, and fingerlike deposits in the Todilto limestone. A study of the structural, stratigraphic, and compositional relations of these deposits provides clues to their genesis.

Typically the semitabular deposits are figuratively suspended within the sandstone units. Most are not bounded by impermeable barriers, and sharp internal grade variations commonly transect sedimentary structures. In addition one group of many small deposits transects the contact between Entrada sandstone and

the Todilto limestone. Structurally this group of deposits is more nearly horizontal than the enclosing sedimentary rocks.

Only pre-Dakota tectonic and related structures are known to contain uranium deposits. Intraformational folds in Todilto limestone, and sandstone pipes in the Jackpile sandstone contain some deposits; a broad anticline of low amplitude apparently is coextensive with the long dimension of one large deposit.

An intimate mixture of nonfragmental organic carbon and uranium occurs in many deposits in sandstone and possibly in all deposits of the district. Since the material impregnates the sandstone and forms ore boundaries that cut sharply across sedimentary structures, the organic carbon component was probably derived from a fluid.

It is interpreted that uranium deposition took place near an interface between two solutions, possibly early in the postdepositional history of the rocks, and that one solution was either organic or an aqueous solution that contained an organic substance.

PRIMARY BORATES IN PLAYA DEPOSITS: MINERALS OF HIGH HYDRATION[1]

SIEGFRIED MUESSIG

U. S. Geological Survey, S. 157 Howard Street, Spokane, Washington

The primary borate minerals in nonmarine bedded borate deposits—those of the playa type, and their deformed derivatives—are the high hydrates. Both field and experimental data indicate that the high hydrates are the borate minerals that form stable phases at the lowest temperatures, i.e., under the surface conditions of playas.

From a study of hand specimens of borate minerals from new Turkish borate deposits, Meixner (1953) suggested that the borate minerals having the lowest specific gravity, and hence, highest water content, are the primary minerals.

The role of temperature in the formation of the hydrous borates is shown by solid phases in the system $Na_2B_4O_7$–H_2O (Menzel and Schulz, 1940). As temperature increases, hydration of the solid phase decreases successively from borax ($10H_2O$) through tincalconite ($5H_2O$), kernite ($4H_2O$), to metakernite ($2H_2O$). This suggests that in the temperature ranges considered in the present paper—those of playas—the high hydrate (borax) is the one most likely to form as the primary mineral in nature. Studies of the Ca, Mg, and Ca-Na hydrous borate systems (see Kemp, 1956) suggest that the same statement holds in these systems.

Until recently, only borax and ulexite ($Na_2O \cdot 2CaO \cdot 5B_2O_3 \cdot 16H_2O$) have been known as primary minerals of playa deposits. However, inderite ($2MgO \cdot 3B_2O_3 \cdot 15H_2O$) has recently been found as a primary mineral in Argentina and primary inyoite ($2CaO \cdot 3B_2O_3 \cdot 13H_2O$) occurs in Peru. These four minerals are the high hydrates of their respective mineral series. None of the lower hydrates is known as primary minerals in nonmarine bedded deposits.

PHYSICAL AND CHEMICAL ENVIRONMENT OF ILLINOIS-KENTUCKY FLUORSPAR DEPOSITS

M. P. NACKOWSKI

Dept. of Mining and Geological Engineering, University of Utah

The Illinois-Kentucky fluorspar deposits are epigenetic and include vein deposits, bedding replacement deposits, and mixed deposits as primary varieties. Texturally these orebodies are either coarsely crystalline, banded (coon-tail), or

[1] Publication authorized by the Director, U. S. Geological Survey.

disseminated. A single orebody may include several or only one textural variety. These textural varieties reflect mechanism of deposition and nature of physical environment at point of deposition.

Physical guides to the fluorspar deposits are structural and stratigraphic. The structural locii are principally fractures, solution channels, and sedimentary channels. These define the plumbing system through which mineralizing fluids flowed. The solution channels developed at the intersection of fractures and limestones immediately overlain by sandstone aquifers. Some developed in limestone beneath sandstone sedimentary channels. The stratigraphic locus is the interval that includes Mississippian lower Chester and upper Meramec limestone formations. These are principally the Fredonia formation, the Downey's Bluff member of the Renault formation, and the Levias formation.

The chemical environment fixed the positions along the plumbing system at which the orebodies formed. Chemical equilibrium was upset when the mineralizing fluids encountered groundwater in the Sandstone formations and in solution channels of underlying limestone formations of the lower Chester and upper Meramec sequence. Fluorspar, silica, and other minerals were deposited by direct precipitation and by replacement of limestone as a consequence. Dilution of mineralizing fluids by ground water, and the change in temperature gradient upon contact with excess ground water are considered the major chemical factors governing formation of the fluorspar deposits.

USE OF WATER-WELL DATA IN INTERPRETING THE OCCURRENCE OF UPPER CRETACEOUS AQUIFERS IN NORTHEASTERN LYON COUNTY, MINNESOTA

H. G. RODIS

U. S. Geological Survey, St. Paul, Minn.

Study of the geology and ground-water resources of Lyon County, in southwestern Minnesota, has included the collection and interpretation of numerous records of farm wells, the majority of which tap Cretaceous sandstone aquifers. It was assumed that most farm wells are completed in the uppermost few feet of the water-bearing bed tapped. By applying simple statistical methods to study the vertical and geographic distribution of well-bottom elevations, it has been possible to outline the general extent of the Cretaceous aquifers and to suggest a possible depositional environment.

The Upper Cretaceous sedimentary rocks of northeastern Lyon County rest on Precambrian granite and are covered with a thin veneer of glacial drift. The Cretaceous sandstones are essentially flat lying and occur at several distinct horizons. They are interbedded with unconsolidated dark-bluish-gray shales and yield relatively soft water under artesian conditions. In the vicinity of the flanks of a granite "high" in the northeastern corner of the county the aquifers are considerably more numerous than in a deeper depositional basin to the southwest, suggesting that the sands may have been deposited during a transgression of the Cretaceous sea.

COLUMBIUM-RARE EARTH-TITANIUM MINERALIZATION AT ST. JOSEPH DU LAC, OKA AREA, TWO MOUNTAINS COUNTY, QUEBEC

CHARLES B. SCLAR AND MARK G. SMERCHANSKI

Battelle Memorial Institute, Columbus, Ohio; Consulting Mining Geologist, Winnipeg, Manitoba

Columbium- and rare earth-bearing perovskite occurs in sharp-walled veins and in an irregular-shaped body enclosed in alnöite of probable Monteregian af-

filiation which has intruded Grenville (?) silicated calcite marble. The rare earth elements in the perovskite are principally cerium and lanthanum.

The perovskite-bearing veins range in thickness from 1 mm to 25 cm. The vein material is a compact purplish-black fine-grained perovskite-rich rock with a subconchoidal fracture and a submetallic luster. It is composed dominantly of fine-grained granular and tiered dendritic aggregates of perovskite and subordinately of variable amounts of magnetite, titaniferous spinel, calcite, biotite, olivine, and melilite. The irregular perovskite-rich mass is a combined stockwork and disseminated replacement deposit of perovskite, magnetite, and titaniferous spinel in the alnöite intrusive.

The mineralization appears to be genetically related to the alnöite. The perovskite is probably of deuteric origin and was introduced principally by replacement and subordinately by fracture filling.

Both the vein perovskite and the perovskite in the mineralized alnöite have been partially altered to leucoxene. Analytical data indicate that the leucoxene is enriched in columbium, cerium, and lanthanum, and that there is a partition between cerium and lanthanum during leucoxenization.

Associated with the alnöite intrusive is a relatively small mass of carbonatite which contains columbium and the cerium group of rare earth elements. The carbonatite is composed dominantly of fine-grained ferruginous dolomite, and it contains minor amounts of perovskite and pyrochlore.

MANGANESE ORES OF THE NSUTA DEPOSIT, GHANA

R. K. SOREM, AND E. N. CAMERON

Department of Geology, University of Wisconsin, Madison, Wisconsin

Mineragraphic and X-ray investigations of manganese ore from the highly productive deposits of Nsuta, Ghana, indicate that the principal manganese oxide minerals are oxides of the gamma-MnO_2 type, cryptomelane, pyrolusite, and lithiophorite. Goethite is closely associated with manganese oxides in some of the ore. Nonmetallic impurities identified are muscovite, quartz, garnet, zircon and amphibole.

Oxide-rich ore has formed by three principal mechanisms: replacement, filling of fractures and other openings, and leaching of impurities from low-grade ore with or without addition of manganese oxides. Replacement ore has formed at the expense of gondite, muscovite-gondite, muscovite-rich rock, and perhaps other rock types. Such ore consists predominantly of gamma-MnO_2 and cryptomelane, but pyrolusite and lithiophorite are present in some specimens. Fillings of fractures and other openings consist predominantly of gamma-MnO_2 and cryptomelane in various proportions. Pyrolusite is abundant in many specimens, and lithiophorite is present in some. Colloform textures are common features. Ore formed by leaching of impurities consists mainly of gamma-MnO_2 and cryptomelane. Goethite is present locally in all three types of ores.

In most specimens, gamma-MnO_2 and cryptomelane are early minerals, but there is no fixed paragenetic sequence of the oxide minerals. Two or more generations of various oxides are present in many specimens.

The manganese oxides appear to be of secondary origin. Mineral relationships indicate that oxide formation has involved repeated migration and precipitation of manganese from ground waters that have intermittently varied in composition. Colloidal deposition appears to have played a prominent role in oxide formation.

TIME RELATIONS OF INTRUSION, FAULTING, AND MINERALIZATION AT LEADVILLE, COLORADO

OGDEN TWETO

U. S. Geological Survey, Denver Federal Center, Denver, Colorado

Although the pre-ore age of some faults at Leadville has been recognized previously, many prominent north-trending faults have been classed as post-ore, as have lesser faults of other trends. Recent work indicates that almost all faults were in existence at the ore stage, although many underwent renewed movement later.

Most faults of Leadville and neighboring area to the north formed in Laramide time, during the period of porphyry emplacement. Of the numerous porphyries recognized, about 15 can be fitted into an intrusive sequence. Using this sequence as a time scale, formation of successive fault systems and development of the present fault pattern can be traced. Some faults of northerly and easterly trends had developed when the earliest porphyry, the Pando ("White" porphyry), was emplaced. Many more faults, including elements of an important northeast-trending system, existed when the succeeding Elk Mountain and Sacramento porphyries, the earliest members of the Gray porphyry group, were introduced. The present fault pattern was almost complete by the time emplacement of later Gray porphyries such as the Johnson Gulch and Lincoln was completed. The latest porphyry of the Gray porphyry group obliterated faults, including a segment of the major Weston fault.

All these porphyries are of pre-ore age as they are hydrothermally altered and locally mineralized. It follows that most of the faults existed at the time ore was deposited. Thus they could, and evidently did, influence the distribution of ore. This relation calls for a new approach to exploration and adds new possibilities for discovery of ore.

ZEOLITIC ALTERATION OF TUFFACEOUS SEDIMENTS AND ITS RELATION TO URANIUM DEPOSITS IN THE KARNES COUNTY AREA, TEXAS

ALICE D. WEEKS, BETSY LEVIN AND ROBERT J. BOWEN

U. S. Geological Survey, Washington, D. C.

Mineralogic and chemical studies of the uranium deposits in the Karnes County area of the Texas Coastal Plain show that the tuffaceous sediments of the Jackson formation (late Eocene) have been altered zeolitically. Uranium deposits are chiefly in the upper part of the formation. No zeolite was found in the Claiborne group below the Jackson or in the Catahoula tuff above it in the Karnes area. The Claiborne and basal part of the Jackson are glauconitic whereas the upper part of the Jackson is non-glauconitic. The zeolite is huelandite, identified by X-ray diffraction study of the clay size fraction of the rock. Thin sections show low birefringence and fine grained interstitial huelandite. It probably developed from alteration of glass shards, volcanic rock fragments, and feldspar grains.

The elongate area of zeolitically altered Jackson formation encloses the principal uranium deposits of western Karnes and eastern Atascosa Counties. Here the Falls City and Fashing faults of the Mexia fault zone form a warped block. A working hypothesis for the origin of the uranium deposits is that tuffaceous sediments of the Jackson formation were altered by alkaline ground water. This produced the huelandite and released silica and trace elements from the tuff. The trace elements were redistributed and concentrated locally in reducing environ-

ments caused by plant fragments, petroleum, or by H_2S-bearing solutions that came from the Edwards limestone along faults.

Farther south the Catahoula tuff is altered zeolitically and contains some uranium minerals. "Tridymite" reported in the Catahoula may be huelandite.

LIQUID OF INCLUSIONS IN SULFIDES FROM TRI-STATE (MO.-KANS.-OKLA.) IS PROBABLY CONNATE IN ORIGIN

DONALD E. WHITE

Menlo Park, California

Newhouse and others have shown that liquid of inclusions in sphalerite and galena of the Tri-State district (Mo.-Kans.-Okla.) and some other base-metal localities consists of saturated or nearly saturated chloride brines. Qualitative analyses have shown dominance of Na, Ca, and Cl ions; K, Mg, and various forms of S and combined CO_2 are minor or nearly absent. Similarities between these solutions and oilfield brines of the Na-Ca-Cl type have been recognized.

Analyses of most recognized types of highly mineralized waters or waters that may have come from great depth in the earth's crust have been reviewed as a part of the revision of Clarke's "Data of Geochemistry." The qualitative similarity between the compositions of these liquid inclusions and the Na-Ca-Cl type of oilfield brine is indeed striking. It is also significant that no evidence has been found for a volcanic or magmatic type of water of similar composition. Present evidence suggests strongly that the liquid inclusions and presumably, therefore, the mineralizing solutions are connate in origin.

Oilfield brines of the Na-Ca-Cl type seem to have relatively low K/Na, Li/Na, and F/Cl ratios; intermediate Mg/Ca, I/Cl, and B/Cl; moderately high Br/Cl and total combined nitrogen; and nearly the lowest SiO_2 content of all natural waters. Quantitative determinations of minor components, and isotopic analyses of D and O^{18} of liquid inclusions should be made to support or refute a connate origin for the water.

STRUCTURAL BELTS AND MINERAL DEPOSITS OF NORTHWESTERN ARGENTINA *

F. B. WHITING

Cfa. Minera Aguilar, S. A.—Tres Cruces—Jujuy—República Argentina

In northwestern Argentina three belts which differ in topography differ also in structure, in type of igneous activity, and in their selection of mineral deposits. The belts trend northnortheast parallel to the main line of the Andes Mountains.

The easternmost belt is a lowlying area of gentle folds, with a fairly complete stratigraphic section, no acidic intrusives, very little basic intrusive rock, no volcanic activity, and few metal deposits.

The central belt is a zone of strong regional thrust-faulting and uplift, and is the main zone of movement between the lowlands to the east and the high Andean plateau to the west. The sedimentary column is less complete, as the area was uplifted during much of geologic time. Granitic intrusions are spread throughout the belt. Volcanic activity is lacking. Mineral deposits consist of numerous veins with lead, zinc, silver, copper, barite, and other metals. The Aguilar mine, largest in Argentina, is situated within this belt.

The westernmost belt is a high plateau with many Precambrian areas, a scanty Palaeozic and Mesozoic section, and very abundant volcanos. Late granites are

* This abstract has been approved for publication by company officials.

absent. Mineral deposits are copper and iron, associated with Precambrian granodiorites, and silver, tin, gold, antimony, borax, sulphur, etc., associated with the young volcanic rocks.

Abstracts of Papers to be read by title, Society of Economic Geologists, St. Louis Meeting, Nov. 6–8, 1958.

THE ORIGIN OF THE MISSISSIPPI VALLEY TYPE DEPOSITS

G. C. AMSTUTZ

Missouri School of Mines and Metallurgy

The three conventional theories on the origin of the Mississippi Valley type mineral deposits are marked 1, 3, and 4 in the following scheme:

1—syngenetic-supergene
2—syngenetic-hypogene
3—epigenetic-supergene
4—epigenetic-hypogene

The syngenetic-hypogene possibility may explain the origin of the large disseminated deposits of the Mississippi Valley type best and appears to overcome the difficulties met with by the conventional theories. This new approach accepts the syngenetic character of the ore just as does theory 1. The syngenetic nature is mostly shown by the pre- and syn-diagenetic sedimentary fabrics which were analyzed in detail, and by the lack of replacement criteria. It brings the ore fluid in from below as hydrothermal solutions which reached the surface and dumped their mineral wealth into the ocean as submarine exhalations.

There are good reasons to assume that in general a large portion of hydrothermal ore fluids reaches the surface of the earth and that there are many gradual transitions in both physico-chemical conditions and mineralogic compositions and between magmatic and sedimentary rock and ore formations. We are thus more often dealing with transitions rather than only convergences between these two extreme types of rock and mineral geneses.

As other stable shield areas the Middle West shows frequent rejuvenation of Precambrian polygonal fracture systems which have served as channelways for the gradually decreasing de-gassing of the earth, leading to mineralizations at least all through Paleozoic times, and thus over much longer periods of time than in orogenic belts.

NIOBIUM-TITANIUM-RARE EARTH MINERALS OF RAVALLI COUNTY, MONTANA, AND LEMHI COUNTY, IDAHO

E. WM. HEINRICH, A. A. LEVENSON, J. M. AXELROD AND CHARLES MILTON

University of Michigan, Ann Arbor, Michigan, Dow Chemical Co., Freeport, Texas, and U. S. Geological Survey, Washington, D. C.

Calcitic (marble) veins up to several feet in width, occurring north and south of the Bitterroot Mountain continental divide in Ravalli County, Montana, and Lemhi County, Idaho, contain notable quantities of niobium, titanium, and rare earths. The mineralized area trends roughly northwest and is 3 or 4 miles wide and 17 miles long. In Montana columbite, monazite, ancylite, and allanite, and in Idaho ilmenite, rutile, ilmenorutile, monazite, ancylite, and allanite are found in

these veins. With the columbite is fersmite, calcium niobate, known elsewhere only from Russia. Other minerals present in these veins are dolomite, quartz, pyrite, pyrrhotite, chalcopyrite, molybdenite, apatite, magnetite, hematite, barite, and various silicates such as biotite, chlorite, serpentine, actinolite, and glaucophane. The country rock is a series of schists and gneisses, Belt or older in age.

Fersmite characteristically occurs as sharply bounded inclusions in columbite. It is dark brown, translucent, and in polished section, darker than columbite. Ilmenorutile is intergrown with ilmenite. Radioactivity is shown by allanite, but not in the monazite specimens tested so far.

Spectrographic analysis of the columbite indicates little if any tantalum, and that of the ilmenorutile gives 13% Nb, $< 0.1\%$ Ta, $46\% \pm$ Ti.

The rare-earth carbonate minerals (ancylite, bastnaesite?) are intergrown with other carbonates, so that their isolation for study is difficult.

Mineralogical data are given for a large number of individual prospects and occurrences.

*ALKALI FELDSPARS FROM ORE AND NON-ORE BEARING PARTS OF SOME INTRUSIVE PORPHYRIES**

FREDERICK J. KUELLMER, JOHN H. CARMEN, AND JACQUES R. RENAULT

New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico

Orthoclase feldspars from the Castle Dome, Copper Cities, and Inspiration mining areas, and the Schultze granite, near Miami, Arizona, have been studied. Sixteen analyses of orthoclase from the various rock units show the average bulk composition of the alkali feldspar is Or_{70} (range: Or_{69} to Or_{72} in the non-ore areas, and in ore areas (areas of moderate hydrothermal alteration) Or_{67} (range: Or_{62} to Or_{82}). On the basis of the ($\bar{2}01$) intensity-ratios of all (59) orthoclase perthite samples, the estimated bulk composition ($\pm$ 10 wt.%) and range of measurements for each area are: Schultze granite, Or_{96} (Or_{54} or Or_{75}); Castle Dome ore, Or_{90} (Or_{78} to more than Or_{90}); Castle Dome non-ore, Or_{72} (Or_{66} to Or_{82}); Copper Cities ore, Or_{82} (Or_{69} to more than Or_{90}); Copper Cities non-ore, Or_{79} (Or_{64} to more than Or_{90}); Inspiration ore, Or_{63} (Or_{51} to Or_{83}); and Inspiration non-ore, Or_{70} (Or_{61} to Or_{78}). Preliminary X-ray diffractometer studies while heating to 800° C, suggest that the orthoclases from the ore areas are in a higher temperature state than those of the surrounding non-ore areas including the Schultze granite. Orthoclase perthites from the ore areas show a smaller ($\bar{2}01$) thermal expansion (more like sanidine than microcline) and/or a greater remixing of the perthite phases by heating.

REDBED URANIUM OCCURRENCES IN PENNSYLVANIA

JOHN F. MCCAULEY

Columbia University, New York, N. Y.; Pennsylvania Geologic Survey, Harrisburg, Pa.

More than forty uneconomic copper-uranium occurrences have been reported in Pennsylvania. The majority are localized in the upper Devonian Catskill formation in the north central and northeastern parts of the state within the gently deformed rocks of the Allegheny Plateau province.

The Catskill formation consists of predominently red siltstones and shales with numerous gray to green sandstones, interpreted as channel deposits. Three broad subdivisions can be made: 1) an upper zone, 400 feet thick, containing

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mostly gray to green sandstones; 2) a middle zone, 1000 feet thick, containing predominently red shales and siltstones; and 3) a lower zone, 500 to 800 feet thick, consisting of alternating gray channel deposits and red shales and mudstones. Carbonaceous material is abundant in the upper and lower zones occurring in the form of thin seams and stringers rarely more than an inch in thickness. Analysis indicates that the material approaches bituminous coal in composition. Mineralization is associated with the material of the lower zone.

Sulfides fill cracks and replace plant cells. Pyrite, chalcopyrite, bornite, galena, chalcocite, and covellite are present along with malachite and azurite and the secondary uranium minerals uranospinite and meta-zeunerite. No primary uranium minerals have been recognized. Analysis indicates that primary uranium may occur in the form of an urano-organic compound. Chalcopyrite occurs as oriented exsolution laths within bornite suggesting an elevated temperature of formation.

The genesis is attributed to moderately hot rising solutions. Lateral migration through the network of permeable stream channels at the base of the formation influenced final localization.

ALTERATION IN PART OF THE UNITED STATES MINE, WEST MOUNTAIN (BINGHAM) DISTRICT, UTAH

JAMES D. STEPHENS AND L. B. SAND

Department of Mineralogy, University of Utah, Salt Lake City, Utah

A study of the alteration in the United States Mine determined that sufficient correlation of alteration with proximity to ore could be detected and used as an additional guide to underground exploration. Samples were collected for a distance of 110 feet along a bedding plane fault in the Highland Boy limestone member of the Oquirrh quartzite. Ore bodies are located on cross-cutting fissures at each end of this sampled interval.

The lead-zinc ore was emplaced in limestone and partly into the quartzite footwall. Progressive color changes in the alteration along the fault range from a dark green in ore through light green and grey to almost completely white at a distance of forty feet from ore.

Spectrographic and chemical analyses of the bulk samples showed Fe'', Fe''', Al_2O_3, K_2O, and trace contents of Mo, Cu and Ag to increase toward ore: Na_2O and the trace content of zirconium to decrease toward ore: with Cao and Mgo variable.

X-ray diffraction analysis revealed the following generalized sequence of clay alteration away from ore: 0–5′, ore with talc; 5–10′, talc and pyrite; 10–20′, phlogopite with some pyrite; 20–40′, Fe-Al montmorillonite; 40–60′, Mg-Al montmorillonite; $>$ 60′, Al-montmorillonite. Variations exist in the alteration from footwall to hanging wall across the fault, but do not affect the general mineral trends. Micas, talc, and dolomite were more concentrated in the footwall, whereas montmorillonite was concentrated in the limestone hanging wall.

MINERALOGY AND GEOCHEMISTRY OF THE URANIUM DEPOSITS OF THE GRANTS DISTRICT, NEW MEXICO

ALICE D. WEEKS AND ALFRED H. TRUESDELL

U. S. Geological Survey, Washington 25, D. C.

In the Grants district uranium deposits occur in both limestones and sandstones. The deposits in sandstone of the Morrison formation here are characterized by lower vanadium and higher molybdenum content than in Uravan, Colo.

Some deposits contain fewer coalified logs or megascopic fragments of wood. The host rocks are highly feldspathic and lithic sandstones with conspicuous kaolinite alteration. The uranium occurs chiefly in black organic coatings on the sand grains and is mainly U^{+6} except locally where coffinite and uraninite form high-grade ore. Häggite was found in one mine. Much ore is deficient in vanadium to complex the uranium; and the common uranyl minerals are uranophane, hydrous oxides, and phosphates. The principal ore mineral in a Dakota sandstone deposit is carnotite.

The primary ore minerals in the Todilto limestone are uraninite and häggite, with a little coffinite and paramontroseite accompanied by barite, pyrite, galena, and, locally, fluorite. Variations in V:U ratio are reflected by the relative abundance of tyuyamunite compared to uranophane and uranyl phosphates, sulfates and carbonates. The lower part of the Todilto contains ostracodes which probably with other organic remains provided the reducing environment favorable for precipitation of uranium and vanadium. The acid insoluble fraction of the limestone ranges from 8 percent near the base to as much as 75 percent in the upper part. It consists of quartz, feldspar, montmorillonite, euhedral zircon, and "books" of biotite and represents, at least in part, volcanic ash. Leaching of the volcanic ash is a possible source of the uranium.

SCIENTIFIC NOTES AND NEWS

J. LAURENCE KULP, head of the Geochemistry Laboratory of Columbia University, has been appointed Professor of Geochemistry. He will spend the coming academic year at Oxford University as a National Science Foundation Senior Postdoctoral Fellow.

JOSEPH HERBERT WATSON was elected President of the Institution of Mining and Metallurgy for the session 1959–60 in succession to MR. J. B. DENNISON, and will take office in May next year. Dr. Watson was awarded the M.B.E. in 1945 and the C.B.E. in 1957.

W. T. HOLSER recently associated with G. C. KENNEDY at the Institute of Geophysics, U.C.L.A. has accepted a research position in the Geology Division at California Research Corporation's La Habra Laboratory.

The U. S. INTERIOR DEPARTMENT will build a new helium plant in the Keyes natural gas field, Cimarron County, Oklahoma, at a cost of $12,000,000.

The VEMA, a diesel-powered three-masted research vessel maintained by Columbia University's Lamont Geological Observatory, returned to New York from a 10-month scientific voyage to collect data specifically for the International Geophysical Year. The ship covered nearly 34,000 miles. Among the data collected were the effects of radioactive fallout on the chemical contents of ocean water and marine life, the geologic structure of the continents and ocean basins, the circulation of ocean waters, and the nature and origin of deep sea plant and animal life and sediments. DR. MAURICE EWING served as expedition leader.

The U. S. GEOLOGICAL SURVEY has issued a report on oil exploration north of arctic circle which is a detailed narrative on "Exploration of Naval Petroleum Reserve No. 4 and adjacent areas, northern Alaska, 1944–53." This report was published by the Department of the Interior in cooperation with the Department of the Navy. It outlines the background of events that resulted in the initiation of Pet. 4, describes the organization, the long-range planning, the progress, and finally the accomplishment in terms of the original objective—"To appraise the oil possibilities of Naval Petroleum Reserve No. 4 and surrounding areas."

The U. S. GEOLOGICAL SURVEY announces publication of a geologic map of the northern Tuwayq quadrangle, Kingdom of Saudi Arabia. The quadrangle is located in the northeastern part of Saudi Arabia and includes the city of Riyad, capital of the Kingdom. Geologic formations range from Precambrian to Quaternary. The map was prepared by the U. S. Geological Survey and RICHARD A. BRAMKAMP and LEON F. RAMIREZ of the Arabian American Oil Company, under the joint sponsorship of the Kingdom of Saudi Arabia and the U. S. Department of State. This is the second geologic map of Saudi Arabia to be issued. Price, $1.00.

The U. S. GEOLOGICAL SURVEY is to have a third building at Menlo Park, California, which is to house the Survey's topographic mapping operations on the West Coast.

The U. S. GEOLOGICAL SURVEY sent out nearly 200 geologic field parties this past summer.

J. J. BRUMMER, formerly with Northwestern Explorations, Ltd., Vancouver, has joined the staff of Kennco Explorations (Canada), Ltd., Toronto.

TRAVIS P. LANE has joined the Arizona Department of Mineral Resources, with offices at Phoenix.

JOHN C. HAGEN, geologist for Ozark Ore Co., Missouri, has been assigned by M. A. Hanna Co. to St. John d'el Rey Mining Co. to investigate with other engineers St. John's gold and iron ore resources in Brazil.

JAMES A. PIKE, British Columbia manager of Newmont Mining Corp. of Canada, Ltd., has been elected president of British Columbia and Yukon Chamber of Mines for 1958.

RICHARD N. HUNT has retired as vice president and chief geologist for United States Smelting and Refining Co., but will continue as a director and will also be on the board of Hecla Mining Co. He is succeeded by RALPH TUCK, formerly assistant chief geologist, who has been designated chief geologist—western operations.

JOHN E. HAMMELL, Canadian mining pioneer, died last May at the age of 82 at his Oakville, Ontario, home. Mr. Hammell was known particularly for his role in the development of Flin Flon mine in northern Manitoba, which became the Hudson Bay Mining and Smelting Co., and for the opening up of the Howey at Red Lake and the Pickle Crow.

Behre Dolbear and Co., consultants in the mineral industries, announce that DR. ARMINE F. BANFIELD, after serving for eight years as an associate, was admitted to partnership in the firm on July 1. Dr. Banfield is at present in Iran on a professional mission.

THOMAS W. MITCHAM, consulting mining engineer and geologist, has moved his office from Flagstaff to Tucson, Arizona. In addition to conducting his consulting business, he will teach two graduate courses in geology at the University of Arizona on a part-time basis.

J. D. BATEMAN has resigned his position as Chief Geologist and Vice President of Ventures Ltd. and has set up an office in Toronto as consulting geologist.

THE 2ND CARIBBEAN GEOLOGICAL CONFERENCE will take place January 5–9, 1959, at Mayaguez, Puerto Rico, at the invitation of the University of Puerto Rico and the Economic Development Administration of the Commonwealth of Puerto Rico. Sessions will be held on general problems of Antillean structure, local geology of various parts of the Caribbean, and economic geology. Field trips will be arranged. Accommodation is extremely limited. Enquiries should be addressed to Prof. John D. Weaver, Chairman of the Committee, Section of Geology, University of Puerto Rico, Mayaguez, Puerto Rico.

VINTON H. CLARKE, Associate Member of Behre Dolbear & Co., is in Kerman, Iran, with Dr. A. F. Banfield, organizing a mineral reconnaissance of 47,000 square miles.

The U. S. Atomic Energy Commission announced that at June 30, 1958, U. S. uranium ore reserves were 78.5 million tons of 0.27% U_3O_8, of which New Mexico had 52.8, Wyoming 11.1, Utah 5.1, Colorado 3.7, Arizona 1.4, others 4.4 million tons. Ore fed to processes was 2,471,000 tons averaging 0.26% U_3O_8. Eighteen uranium plants were in operation with others to come. The Government paid $9.34 per pound for concentrates. In June the tons of ore treated per day was 15,700. Ore receipts for the first 6 months totaled 2,440,000 tons. Uranium ore stockpiles at June 30 were 1,956,531 tons averaging 0.29% U_3O_8.

The California Institute of Technology, Pasadena, Calif., with the support of the U. S. Coast and Geodetic Survey, and the National Science Foundation, will install 100 small, inexpensive earthquake recorders developed by Caltech engineers in Los Angeles and San Francisco metropolitan areas within a year to help determine which soils absorb earth shocks better than others. The information obtained will be of particular interest to building officials, especially in reference to commercial structures and bridges. The devices will be placed on different types of geological formations, both soft and firm. The instruments are 8 by 12 inches, weigh 8 pounds, and cost about $100 each. They will be bolted to a basement floor or to a rock and require no maintenance. They are adjusted to record only earth motions in the immediate vicinity that are large enough to cause structural damage. This would be the equivalent of the ground motion within 15 miles of the epicenter of a magnitude 6 temblor or within 50 miles of the epicenter of a magnitude 7 shock. The record is made by a pendulum and needles on an inverted smoked watch glass 2½ inches in diameter. One instrument is being sent to Chile and another to India.

Maurice Ewing and Jack Olivar announce that surface waves from nuclear explosions were detected by Lamont Geological Laboratory seismographs at Palisades, N. Y., nearly a third of the way around the earth. Surface waves were recorded from 9 nuclear test blasts in the Marshall Islands, more than 7,000 miles away, and from 3 tests in Nevada.

Correction: Vol. 53, No. 4, p. 459, bottom of page, the words, "steeper" and "flatter" should be transposed.

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For description of Professor Sampson's method, see Economic Geology, Vol. 51, No. 5, August, 1956.

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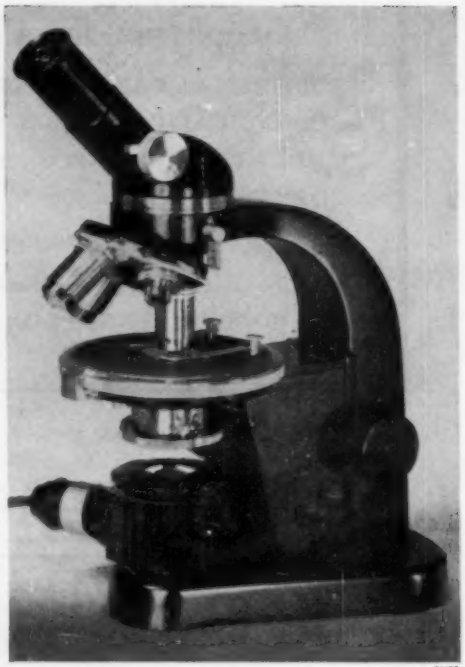

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